ENGINEERING PROPERTIES OF NORMAL AND HIGH STRENGTH CONCRETE CONTAINING PALM OIL CLINKER

FUAD Y. M. ABUTAHA

**THESIS SUBMITTED IN FULFILMENT
OF THE REQUIREMENTS
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY**

**FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR**

2018

UNIVERSITY OF MALAYA

ORIGINAL LITERARY WORK DECLARATION

Name of Candidate: Fuad Y M Abutaha

Matric No: KHA130109.

Name of Degree: PhD.

Title of Thesis: Engineering Properties of Normal and High Strength Concrete Containing Palm Oil Clinker.

Field of Study: Construction Technology and Management.

I do solemnly and sincerely declare that:

(1) I am the sole author/writer of this Work;
(2) This Work is original;
(3) Any use of any work in which copyright exists was done by way of fair dealing and for permitted purposes and any excerpt or extract from, or reference to or reproduction of any copyright work has been disclosed expressly and sufficiently and the title of the Work and its authorship have been acknowledged in this Work;
(4) I do not have any actual knowledge, nor do I ought reasonably to know that the making of this work constitutes an infringement of any copyright work;
(5) I hereby assign all and every right in the copyright to this Work to the University of Malaya ("UM"), who henceforth shall be owner of the copyright in this Work and that any reproduction or use in any form or by any means whatsoever is prohibited without the written consent of UM having been first had and obtained;
(6) I am fully aware that if in the course of making this Work I have infringed any copyright whether intentionally or otherwise, I may be subject to legal action or any other action as may be determined by UM.

Candidate's Signature Date:

Subscribed and solemnly declared before,

Witness's Signature Date:

Name:

Designation:

ENGINEERING PROPERTIES OF NORMAL AND HIGH STRENGTH CONCRETE CONTAINING PALM OIL CLINKER

ABSTRACT

Utilization of locally available waste materials to replace conventional concrete materials has gained considerable attention in the past two decades. Palm oil clinker (POC) is a lightweight waste material generated from the palm oil industry in Malaysia. POC, when crushed possesses the potential as aggregates for concrete production. Experimental investigation on the usage of POC as a partial and full replacement of the natural aggregates and filler material was carried out in this study. Normal and high strength concrete of 40 and 90 MPa respectively, were the design strength for the purpose of this study. Department of environment (DOE) and Sherbrooke mix design methods were adopted to produce the normal and high strength concrete, respectively. Crushed POC was partially and fully used to replace natural aggregates i.e. fine and coarse. The percentage of POC replacement used are 0%, 20%, 40%, 60%, 80% and 100% of the total volume of fine and coarse aggregate, separately. Particle-packing (PP) method was then adopted for the mixes where coarse aggregate was substituted with POC. To enhance the engineering properties of POC concrete, addition of Palm oil clinker powder (POCP) was then incorporated to the mixes as a filler material to fill up the voids of POC, while maintaining the other mix constituents. Fresh and hardened properties were investigated for the concrete mixes with and without POCP and the results were compared to the control concrete, which was prepared using natural aggregates. POC, being highly porous had a negative effect on the fresh and hardened concrete properties when coarse aggregate was substituted with POC. Meanwhile, the replacement of the natural sand with POC fine had insignificant effect on fresh and hardened properties of concrete. The results also revealed that incorporating additional POCP to normal and high strength POC concrete improved the engineering properties as well as the durability performance. Therefore, there is a great potential towards utilization of POC in the normal concrete production.

This approach offers an environmental friendly solution to the ongoing challenge of palm oil mill waste materials.

Keywords: High strength concrete**,** Palm oil clinker, Particle packing, Sustainability, Waste material.

SIFAT SIFAT KEJURUTERAAN TERHADAP KONKRIT NORMAL DAN KONKRIT BERKEUPAYAAN GALAS TINGGI YANG MENGANDUNGI KLINKER MINYAK KELAPA SAWIT

ABSTRAK

Penggunaan bahan-bahan buangan tempatan yang sedia ada untuk menggantikan bahan konkrit konvensional telah mendapat perhatian dalam dua dekad yang lalu. Palm Oil Clinker (POC) adalah bahan sisa ringan dijana daripada industri minyak sawit di Malaysia. POC, apabila dihancurkan mempunyai potensi sebagai agregat untuk pengeluaran konkrit. Kajian eksperimen mengenai penggunaan POC sebagai pengganti separa dan penuh dengan agregat semula jadi dan bahan pengisi telah dijalankan. Kekuatan normal dan tinggi bagi konkrit masing-masing adalah di antara 40 dan 90 MPa, adalah kekuatan reka bentuk untuk tujuan kajian ini. Department of Environment (DOE) dan Sherbrooke telah digunakan untuk menghasilkan konkrit berkekuatan normal dan tinggi masing-masing. POC yang dihancurkan sebahagian dan sepenuhnya digunakan untuk menggantikan agregat semula jadi iaitu halus dan kasar. Peratusan penggantian POC digunakan adalah 0%, 20%, 40%, 60%, 80% dan 100% daripada jumlah agregat halus dan kasar, secara berasingan. Particle Packing (PP) telah diterima pakai bagi campuran di mana agregat kasar digantikan dengan POC. Untuk meningkatkan ciri-ciri kejuruteraan POC konkrit, penambahan Palm Oil Clinker Powder (POCP) telah digabungkan kepada campuran sebagai bahan pengisi untuk mengisi lompang POC, disamping mengekalkan juzuk campuran lain. Sifat-sifat baru dan keras telah disiasat bagi campuran konkrit dengan dan tanpa POCP dan keputusan telah dibandingkan dengan konkrit kawalan, dimana ia telah disediakan dengan menggunakan agregat semula jadi. POC yang sangat berliang mempunyai kesan negatif ke atas sifat-sifat konkrit baru dan keras apabila agregat kasar diganti dengan POC. Sementara itu, penggantian pasir semula jadi dengan POC halus tidak mempunyai kesan yang besar ke atas sifat-sifat baru dan keras konkrit. Keputusan juga menunjukkan bahawa penggabungan tambahan POCP kepada kekuatan normal dan tinggi POC meningkatkan sifat-sifat kejuruteraan serta prestasi ketahanan. Oleh itu, terdapat potensi yang besar ke arah penggunaan POC dalam pengeluaran konkrit biasa. Pendekatan ini menawarkan penyelesaian mesra alam kepada cabaran yang berterusan terhadap sisa minyak kelapa bahan-bahan buangan kilang.

Kata kunci: Konkrit kekuatan tinggi, klinker minyak kelapa sawit, Pembungkusan zarah, Kemapanan, Bahan sisa

ACKNOWLEDGEMENTS

To my father, because I owe it all to you. To my mother, this work could not have happened without your prayers and inspiration. Many thanks for your endless love, support and encouragement! Remarkable merits to all my brothers and sisters who believe that my dream to finish this thesis was more than just a dream.

I would also like to express my special thanks of gratitude to my supervisor Prof. Dr. Hashim Abdul Razak for his invaluable guidance, encouragement, advice and helpful insights to ensure this project complete accuracy.

To University of Malaya and Ministry of Education - Malaysia (MOE) for supporting given through the research grants of UM.C/625/1/HIR/MOHE/ENG/56. Special thanks are also go to the staffs and members of the Concrete Technology laboratory, University of Malaya for their support and relentless help provided throughout the period of research.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

The following symbols and abbreviations are used in this study:

f_r	Flexural Strength
f_{cu}	Cube Compressive Strength
f_{cy}	Cylinder Compressive Strength
f_t	Splitting Tensile Strength
E_c	Modulus of Elasticity
W_C	Unit Weight
ACV	Aggregate Crushing Value
ASTM	American Standard for testing Materials
BA	Bottom Ash
BS	British Standard
CA	Conventional Aggregates
CH	Calcium Hydroxide
CKD	Cement Kiln Dust
C-S-H	Calcium Silicate Hydrate
DEMEC	Demountable Mechanical Strain Gauge
EDX	Energy-Dispersive X-ray
EFB	Empty Fruit Bunches
FA	Fly Ash
GGBS	Ground Granulated Blast-furnace Slag
HPC	High Performance Concrete
HSC	High Strength Concrete
ITZ	Interfacial Transition Zone

LA	Los Angeles
LWA	Lightweight Aggregate
LWAC	Lightweight Aggregate Concrete
LWC	Lightweight Concrete
MOE	Modulus of Elasticity
NC	Normal Concrete
NDT	Non-Destructive Test
NWA	Normal weight Aggregate
NWC	Normal weight Concrete
OPC	Ordinary Portland Cement
OPF	Oil Palm Fibre
OPS	Oil Palm Shell
POC	Palm Oil Clinker
POCP	Palm Oil Clinker Powder
POFA	Palm Oil Fuel Ash
POME	Palm Oil Mill Effluent
PP	Particle Packing
RCPT	Rapid Chloride Permeability Test
RHA	Rice Husk Ash
RM	Malaysian Ringgit
SCC	Self-Compacting Concrete
SCM	Supplementary Cementitious Materials
SE	Structural Efficiency
SF	Silica Fume
SP	Superplasticizer
SP	Superplasticizer

SSD	Saturated Surface Dry
UPV	Ultrasonic Pulse Velocity
W/B	Water to Binder Ratio
W/C	Water to Cement Ratio
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

1.1 General

The construction industry is one of the largest industries in the world. Nowadays, the pace of development of this industry is increasing enormously all over the world especially in the developing countries due to rapid economic and industrial development of infrastructures and standard of living (Bragança et al., 2007). Concrete is the most widely used construction material due to its versatility, economy, strength, availability of raw materials and durability (Akadiri et al., 2013). Concrete can be designed to withstand the harshest environmental conditions while taking on the most inspirational shapes and forms. The consumption of concrete as a construction material in the world is over twice the total consumption of all other building materials including steel, wood, plastic and aluminum. It was reported that the total annual concrete production in the world is over 10 billion tones (Meyer, 2009).

Recently, the use of environmentally friendly and energy saving materials is more urgent than ever. The utilization of solid waste and by-products in construction has gained the attention of many researchers. This interest is a result of various factors such as the ever increasing cost of raw materials and the continuous depletion of natural resources (Mannan and Ganapathy, 2004). In addition, continuous development in the industrial and technological sectors generates high amounts of wastes. These wastes are disposed to dumping sites, causing environmental pollution and hazards (Abeysundara et al., 2009). Thus, these wastes must be eliminated or reduced to protect the environment. One of the basic strategies orchestrated to decrease solid waste problems is the recovery of usable materials from waste, as well as utilization of waste as raw materials (Hussein and Muda, 2012). This approach can be done by exploring ways to use these wastes as an alternative to existing products such as utilization as an aggregate in concrete production

(Jepsen et al., 2001). This alternative would ensure the preservation of the natural resources by mitigating the depletion of rock outcrops that are usually quarried and crushed towards utilization as aggregate in construction work. As a result, many researchers are determined to identify the uses of various waste materials for sustainable development. Developing countries can utilize excessive agricultural waste as partial and full material replacement in the construction industry instead of disposing them conventionally (Mannan et al., 2004). Industrial wastes can be used as raw materials especially in the production of concrete (Halicka et al., 2013). Hence, using waste as aggregates in concrete production may be a suitable approach towards sustainable construction (Senthamarai and Manoharan, 2005). Based on the unit weight, concrete can be classified into three categories namely light, normal and heavy weight concrete. Among these types, lightweight concrete (LWC) is an attractive research topic due to its higher strength to weight ratio than normal weight concrete (NWC). There are several methods of producing LWC. The most popular way is by using lightweight aggregates (LWA). Different natural and artificial LWA are available and the properties of each are different from another.

Palm oil Clinker (POC) is a waste material from agricultural sector. The waste is obtained as a result of palm oil shell incineration in the production of palm oil. It is produced in large quantities in tropical regions. POC is available in the form of solid lightweight material in varying sizes between 20 to 150mm, the large chunk of POC is porous, flaky and irregularly-shaped, with rough and sharp broken edges. POC, when crushed possesses the potential as aggregates for concrete production. The solid wastes and by-products, when properly used, has shown to be a comparable construction raw material (Mannan and Neglo, 2010) . This study evaluates the effect of incorporating POC aggregates i.e. fine and coarse on the engineering properties of normal and high strength concretes. The aim is to examine the applicability of palm oil waste and by-products in terms of its potential application as natural aggregates replacement in concrete towards the sustainability of the construction industry.

1.2 Problem Statement

Generation of large amounts of municipal solid waste is one of the main environmental problems in many industrialized countries (Hwang et al., 2012). The management and treatment of industrial solid waste are some of the great challenges in the world. The agricultural industry has been a mainstay of the Malaysian economy for the past two decades with millions of hectares being planted with oil palm, rubber, paddy, sugar cane, coconut and cocoa (Hosseini and Wahid, 2014). The extraction of useful material from these plants generates various types and forms of waste material, which need to be disposed of appropriately. Generally, they comprise ash, grains, wastewater and shells (Kanadasan and Razak, 2014b).

Malaysia is one of the primary producers of palm oil in Asia. It is the second largest palm oil-producing country in the world, which produces more than half of world's palm oil annually (Mannan et al., 2010) . However, the palm oil industry is also one of the major contributors to the pollution problem occurring in the country. Palm oil processing generates various types of waste that have the potential to be utilized in other industries. These include palm oil clinker (POC), palm oil fuel ash (POFA), oil palm shell (OPS), empty fruit bunch (EFB), palm oil mill effluent (POME) and oil palm fibres (OPF). It was reported that the total production of crude palm oil was more than 18.7 million tons (Halimah et al., 2013). This has been projected to grow because of the ongoing global consumption demand for palm oil. Therefore, recently immense attention has been directed towards dealing with the environmental concerns regarding their usage in the production of concrete (Mateus et al., 2013). Nowadays, the scarcity of natural resources and the rising costs of raw materials have induced researchers to focus more on utilizing solid wastes and by-products as raw material in concrete production (Alnahhal et al., 2017; Katz, 2003; Mannan et al., 2010; Rashid et al., 2012).

High quantities of POC is generated in Malaysian palm oil mills as a waste with no profitable return; hence, this industrial waste can be converted into potential construction materials. Attempts have been made to use these waste materials as aggregates in concrete production (Bashar et al., 2013; Kanadasan and Razak, 2014a; Roslli et al., 2002), but not much works have been reported on the use of POC in concrete related to the engineering properties and durability performance. Previous studies reported that due to the physical properties and the high porosity of POC, the utilization of POC aggregates resulted in lower compressive strength of concrete and no research work has been carried out to enhance the performance of POC concrete. There is a continuous rise in the demand for natural sand, and to find an alternative material that is capable of replacing natural sand is essential towards reducing its high demand (Safiuddin et al., 2007). It was observed that after crushing the clinker, much of the crushed aggregate are fine particles. Due to the availability of this waste as fine in high volume, POC if successfully used as fine aggregate will have more advantages towards reducing a high volume of palm oil mill waste. A limited research studied the use of POC as a replacement for natural fine aggregate (Bashar et al., 2014; Kanadasan and Abdul Razak, 2015a; Kanadasan et al., 2014b). High strength lightweight concrete has a significant advantage over normal weight high strength lightweight concrete due to the reduction of dead load and consequent reduction in construction cost (Tuan et al., 2013). However, not all lightweight aggregates are suitable to produce high strength lightweight concrete. A comprehensive research is necessary to fill the existing knowledge gaps.

The present research program was developed to study the engineering properties and durability performance of normal and high strength POC concretes. This research also addresses the sustainable exploitation of POC by ensuring the proper utilization with a suitable mix design. Further, the important determinant towards ensuring that POC is successful shall be based on environmental advantage.

1.3 Objectives of Study

The aim of this research is to experimentally study the feasibility of incorporating POC in concrete production. The specific objectives of this research are as below:

1. To evaluate the effect of incorporating POC aggregates i.e. fine and coarse on the engineering properties of normal and high strength concrete.
2. To propose a mix design method by incorporating POC as aggregates and powder material in normal and high strength concrete production.
3. To determine the feasibility of using POCP as a void filler material to enhance the performance of POC concrete.
4. To assess the applicability of the proposed mix design to develop structural grade POC concrete.

1.4 Scope of Work

This study is part of an extensive research program on the characteristics of POC incorporated concrete. The experimental research was conducted to study the change in properties of normal and high strength concrete at different replacement levels of natural aggregates i.e. fine and coarse with POC. The experimental program involves a total of 32 concrete mixtures including different substitution levels of POC with natural aggregates. Normal and high strength concrete with a compressive strength of 40 and 90 MPa, respectively, being the design strength for the purpose of this study. Two different mix design methods were employed. The normal grade concrete with a compressive strength of 40 MPa was designed using department of environment (DOE) mix design method with water-cement ratio of 0.53 and slump range of 100±25 mm. The HSC with a compressive strength of 90 MPa was designed using Sherbrooke mix design method with water-binder ratio of 0.30 and slump range of 150±25 mm. The work was divided into two major parts. The first part, crushed POC was partially and fully used to replace the natural aggregates i.e. fine and coarse. The percentage of POC replacement used are 0%, 20%, 40%, 60%, 80% and 100% of the total volume of fine and coarse aggregates, separately. In the second part, Particle-packing (PP) method was then adopted for the mixes where coarse aggregate was substituted with POC in order to measure the voids due to the porosity of POC. To enhance the engineering properties of POC concrete, addition of POCP was incorporated to the mixes as a filler material to fill up the voids of POC while maintaining the other mix constituents. Fresh and hardened properties like workability, fresh and hardened densities, compressive strength, splitting tensile, flexural strength, modulus of elasticity, UPV, water absorption, drying shrinkage and resistance against chloride ions penetration were studied for the concrete mixes with and without POCP and compared with the control concrete which prepared using natural aggregates.

1.5 Significance of the Research

The use of waste material in concrete production not only reduces the landfill waste, but it can create new generation materials for manufacturing concrete mixtures (Jepsen et al., 2001). The economic and environmental benefits are some of the factors that determine the viability of using solid waste. From an economic standpoint, using solid waste is cheaper compared to the costs of using natural resources or even the costs of producing new material. Consequently, natural resources can be preserved and there will be a significant reduction in the discharged waste to the environment (Mannan et al., 2010). The consumption of waste products in the construction industry will not only help to reduce the environmental problems but also provide an alternative to the diminishing natural aggregates (Kanadasan et al., 2014b). The utilization of waste by-products can help to improve the waste management to reduce environmental pollution. Channeling these waste products to other industries to be used would be a creative and resourceful method to increase the productivity of the respective industries (Yoon et al., 2003). The novelty of this study was designed to address the sustainable exploitation of POC by ensuring the proper utilization with a suitable mix design. The aim was to examine the applicability of palm oil waste as a natural aggregate replacement in concrete production towards improving the sustainability of the construction industry. The reduction in cost coupled with the lightweight characteristic will provide a positive contribution to the environment as well as to the economic point of view. One of the benefit of using POC as LWA is the reduction in the dead load of concrete without much loss in the strength of the structure. This condition is possible because LWC can reduce the dead load by as much as 35% and still provide the structural strength (Roslli et al., 2002). The use of POC as LWA in concrete provides several advantages such as handling the declining natural resources, reduction of dead load, production of lighter and smaller pre-cast elements, reductions in the sizes of columns and slab and beam dimensions, higher thermal insulation and better fire resistance. Furthermore, Kanadasan and Abdul Razak (2015a) showed that utilization of POC reduces the cost and energy usage and lowers carbon emission. Correct material selection by considering their complete service lifetime and selecting products with minimal environmental effects could minimize CO_2 emissions by up to 30% (González and Navarro, 2006).

1.6 Organization of Thesis

The structure of this thesis mainly consists of five chapters, a list of references and several appendices. Each chapter covered different components of the research. The summary of each chapter is as follow:

- Chapter one gives a general introduction of the purpose and the basic ideas of the study.

- Chapter two summarized review of relevant literature regarding the development of lightweight concrete, describe the various constituent materials of concrete used in this study and their influence on the properties of the fresh and hardened concrete. This chapter also deals with previous studies regarding sustainability in concrete production.
- Chapter three presents the methodology that was adopted to carry out the selection of materials, testing of concrete, and the experimental methods that have been used. Mix design methods of normal and high strength concrete are also presented in this chapter.
- Chapter four presents the tests results accompanied by an extensive discussion. The discussion is made based on the analysis of all the data obtained from the experiments.
- Chapter five is the final chapter of this thesis, which provides the conclusion that had been made from the test results and discussion.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter presents a review of past research that is relevant to the current study, with the aim of providing sufficient background information to facilitate the understanding and evaluation of this investigation. This chapter also deals with previous studies regarding the sustainability in production of concrete and the utilization of waste materials in concrete production.

2.2 Portland cement

Cement is a material with cohesive properties which make it capable of bonding mineral fragments into a compact whole. Ordinary Portland cement (OPC) is one of several types of hydraulic cements being used throughout the world to produce various types of concrete. OPC is composed primarily of calcium silicate minerals. OPC in the production of concrete have the property of setting and hardening under water by means of hydration reaction, which after hardening restrains its strength and stability(Tennis and Jennings, 2000). The hydration of Portland cement is a sequence of overlapping chemical reactions between clinker components, calcium sulphate and water, leading to setting and hardening. The main hydration product, calcium silicate hydrate (C-S-H), has a complex internal pore structure with a high specific surface area (Tennis et al., 2000).

2.2.1 Physical Properties

The physical properties of cement significantly influence the performance of concrete. The particle size distribution of cement has a great effect on the rheology of paste. Therefore, the cement utilized should be free from the problem of false of setting which affects the mixing procedure after adding water (Ylmén et al., 2009).

2.2.2 Chemical Composition

The chemical analysis of Portland cement has revealed that it mostly consists of various oxide compounds. The major compounds are lime, silica, alumina and iron. In addition, two minor oxides namely, sodium and potassium oxides are of some importance, particularly with regard to alkali-aggregate reaction in concrete. Furthermore, magnesia and sulfuric anhydrite can be present, although they are not beneficial constituents of cement. The calculated quantity of the compounds in cement varies greatly even for a relatively small change in the oxide composition of the raw materials. The typical chemical composition of Portland cement is presented in Table 2.1.

Table 2.1: Typical chemical composition of Portland cement (Paris et al., 2016)

Chemical name	Composition	Mass content (%)
Calcium oxide (Lime)	CaO	60.2 - 68.7
Silicon dioxide(Silica)	SiO_2	18.7 - 24.4
Aluminum oxide (Alumina)	AL_2O_3	2.2 - 6.3
Iron Oxide (Ferrite)	Fe_2O_3	0.2 - 6.1
Magnesium oxide (Magnesia)	MgO	0.3 - 4.8
Sulfur trioxide (Sulfuric anhydrite)	SO_3	1.7 - 4.6
Sodium Oxide and Potassium Oxide (Alkalis)	Na_2O and k_2O	0.05 - 1.2

2.3 Supplementary Cementing Materials (SCM)

Supplementary cementitious materials (SCM) are regularly utilized in concrete mixes to minimize the cement contents, increase strength and improve the durability of concrete through pozzolanic or hydraulic activity. The utilization of these by-products as partial replacement of cement not only inhibit being land-filled but also help to improve the concrete properties in the fresh and hardened states (Paris et al., 2016). Rosković and Bjegović (2005) reported that the reduction of the amount of cement used in mortar and concrete production using natural and waste materials as SCM lowers the atmospheric emission of CO_2, reduces energy consumption, improves several concrete properties with increased service life and conveniently reduces the problems associated with the disposal of these waste materials. Agricultural and industrial waste like rice husk ash (RHA), fly ash (FA), ground granulated blast-furnace slag (GGBS), palm oil fly ash (POFA) and silica fume (SF) are utilized in concrete as SCM. SCM in concrete helps to improve the concrete quality based on strength and durability (Tangchirapat et al., 2007). Incorporation of SCM also reduces heat of hydration and decrease bleeding (Chindaprasirt et al., 2007).

2.3.1 Silica Fume (SF)

Silica fume (SF), also called micro silica is a by-product of ferrosilicon and silicon industry. The amount of quartz decreases at a temperature of 2000°C to produce silicon dioxide vapor, which condenses into an amorphous silica spherical particle as presented in Figure 2.4. SF is collected to be used as a cementious material in high strength concrete production (Sanjuan et al., 2015). SF has been recognized as a pozzolanic admixture which is effective in enhancing the mechanical properties to a great extent. It contributes both pozzolanic and filler effect to the concrete, but most dominantly in filler effect due to its excessively fine particle size. SF can fill the voids between the next larger class particles cement to form a dense material. Furthermore, the addition of silica fume densifies the packing in the interfacial transition zone (ITZ), such that the porosity in this region is substantially reduced (Gesoglu et al., 2016). However, there are number of important practical considerations that must be accounted when using SF in concrete. The main issue associated with SF is the extreme fineness, which causes a high-water demand when mixed with Portland cement. Until a few years ago, 40 MPa concrete was considered to be of high strength, but today, with the use of SF together with superplasticizers, it is quite easier to achieve concrete with high compressive strength in the range of 70-120 MPa (Siddique, 2011). Cheng-Yi and Feldman (1985) stated that mortar with SF exhibits higher strength as compared to cement paste with a similar water -cement ratio. Cwirzen and Penttala (2005) concluded that incorporation of SF to mortar strengthens the bond between the hydrated cement matrix and aggregate in the mix, thereby enhancing the strength.

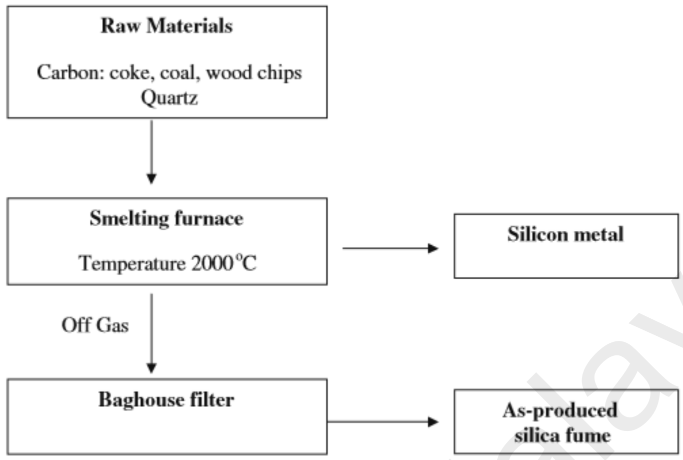


Figure 2.1: Schematic diagram for SF production (Siddique and Khan, 2011)

2.3.1.1 Physical Properties

Primarily, SF contains pure silica in non-crystalline form. The particles of SF are mainly fine spherical with a soaring amount of amorphous silicon dioxide. The high fineness particles act as micro filler and modify the microstructure of cement paste. Generally, SF contains over 90% of SiO_2, with small quantity of alkali, magnesium, and iron oxides. SF particles are extremely small, with more than 95% of the particles finer than 1 µm (Qing et al., 2007).

2.3.1.2 Pozzolanic Reaction Mechanism

The science behind the pozzolanic reaction that makes the particle-binding glue of concrete, which is C-S-H is found in the combination of water and Portland cement. However, the same hydration reaction also creates calcium hydroxide (CH) as a by-product of about 25% of the hydrated Portland cement. CH is a well-crystallized material that has no significant contribution to strength, but it soluble in water and may be slowly removed from concrete by leaching action, which cause efflorescence and increase concrete permeability (Estrela et al., 2000). Moreover, the presence of CH is detrimental to the grout strength of concrete. Porosity induced by CH culminates in high permeability, weak resistance to chemical attacks, poor strength, and hence, shorter life. Replacement of a particular amount of the Portland cement with SF. SF reacts with the CH to produce extra binder material of C-S-H, which is the same as the calcium silicate hydrate produced from Portland cement as shown in Equation (2.2). It is an extra binder that provides silica-fume concrete with enhanced properties.

Hydration reaction: $C_2S \text{ or } C_3S + H_2O \longrightarrow \text{primary } C\text{-}S\text{-}H + Ca(OH)_2$ (2.1)

Pozzolanic reaction: $Ca(OH)_2 + SiO_2 + H_2O \longrightarrow \text{secondary } C\text{-}S\text{-}H$ (2.2)

The pozzolanic effects of SF play a vital role in refining porosity in bulk paste matrix and interfacial transition zone of concrete. The porosity refinement occurs because of the secondary pozzolanic reaction between the SF and $Ca(OH)_2$ making the concrete microstructure denser. Thus, the strength and durability of concrete are improved. The chemical composition of SF is presented in Table 2.2. In general, the effect of SF when partially replaced with Portland cement on the engineering properties of concrete is explained in Table 2.3.

Table 2.2: Chemical composition of silica fume (Hooton and Titherington, 2004; Paris et al., 2016; Sandvik and Gjorv, 1992; Yazıcı, 2008)

Chemical name	Composition	Mass content (%)
Calcium oxide (Lime)	CaO	0.3 - 0.5
Silicon dioxide(Silica)	SiO_2	85 -97
Aluminum oxide (Alumina)	AL_2O_3	0.2 - 0.9
Ferrous (Iron Oxides)	Fe_2O_3	0.4 - 1.0
Magnesium oxide (Magnesia)	MgO	0.0 - 1.0
Sulfur trioxide (Sulfuric Anhydrite)	SO_3	0.0 - 0.4
Sodium Oxide (Alkalis)	Na_2O	0.1 - 0.4
Potassium Oxide	k_2O	0.5 - 1.3
Titanium Dioxide (Titania)	TiO_2	Na
others		0.0 - 1.4

Table 2.3: Effects of SF on the engineering properties of concrete (Paris et al., 2016)

Evaluation method	Effect at 28 days
Compressive Strength	↑ (5 - 20%)
Tensile Strength	↑ (5 - 30%)
Flexural Strength	↑ (5 - 25%)
Permeability	↓ (> 5%)
Workability	↓ (> 5%)
Heat of Hydration	↓ (10%)
Resistance to ASR	↑ (4 - 20%)
Freeze/Thaw Resistance	↑ (10 - 20%)
Sulfate/Chloride Resistance	↑ (5 - 15%)
Resistance to Corrosion	↑ (<20 %)
Setting Time	↑ (5 - 20 %)

De Gutiérrez et al. (2005) investigated the influence of SF on the compressive strength of fibre reinforced mortar using various types of synthetic and natural fibres. The influence of SF incorporation in the pure mortar is presented in Figure 2.2. As observed, addition of SF increased the average compressive strength by 23%. However, fibres in the pure mortar resulted in a decrease in the compressive strength. The reduction in strength was reimbursed by introducing SF into the matrix. Matrix reinforced with glass fibres gained an increase of compressive strength up to 68% when SF was used as a supplementary cementitious material.

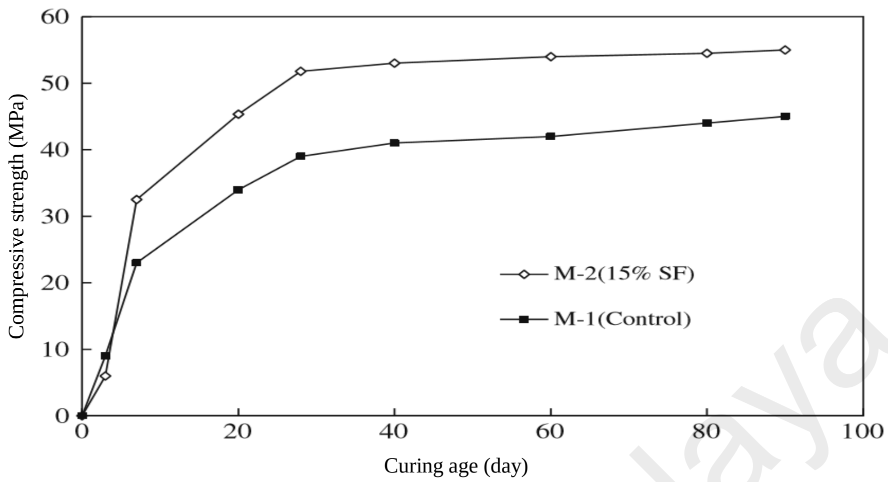


Figure 2.2: Effects of addition of SF in plain mortar (De Gutiérrez et al., 2005)

Bhanja and Sengupta (2005) investigated the contribution of SF on the tensile strengths of HPC. Five concrete mixes, at w/cm ratios of 0.26, 0.30, 0.34, 0.38 and 0.42 were formulated by partial substitution of cement by an equal weight of SF. The amount of SF were 5%, 10%, 15%, 20% and 25% of the total cementitious mix. Figure 2.3 shows that using a very high percentage of SF did not significantly increase the splitting tensile strength and the increase was insignificant beyond 15% of SF.

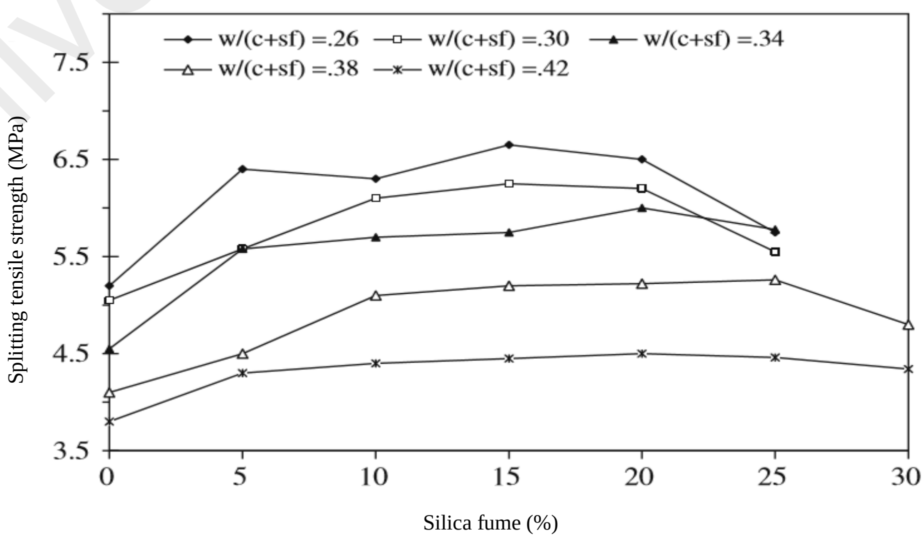


Figure 2.3: Correlation between 28-day split tensile strength and percentage substitution of SF (Bhanja et al., 2005)

2.3.1.3 Durability Performance

Incorporation of SF to concrete enhances the concrete durability by reducing its refined pore structure and permeability, which resulted in decrease the CH content and diffusion of harmful ions, thereby increasing the resistance to sulfate attack (Sanjuan et al., 2015). Improvement in durability will also improve the ability of the SF concrete in protecting the embedded steel from corrosion. Boddy et al. (2003) stated that substitution of SF also lead to a decrease in the reactivity of alkali-silica to the tolerable limit recommended by ASTM C1260. Poon et al. (2006) reported that the resistance of SF concrete to chloride ion penetration is significantly higher than the control concrete. Perraton et al. (1988) investigated the effect of SF on permeability of chloride in concretes. The concretes were prepared with w/b ratio of 0.5 and 0.4. The amount of SF varies from 5 to 20% by weight of cement. The concretes were moist cured for 7 days prior to air drying at a low and normal temperatures for 6 months. A remarkable reduction in the diffusion of chloride-ion in SF concretes was observed, which additionally reduced with increase in incorporation of SF as presented in Figure 2.4. The main reason that may lead to reduction in permeability is that incorporation of SF lead to a substantial pore refinement by transformation of larger pores into lesser one due to the pozzolanic reaction concurrent with cement hydration. Thus, lead to a reduction in the permeability of hydrated cement paste and the porosity of the transition zone between aggregate and cement paste are reduced.

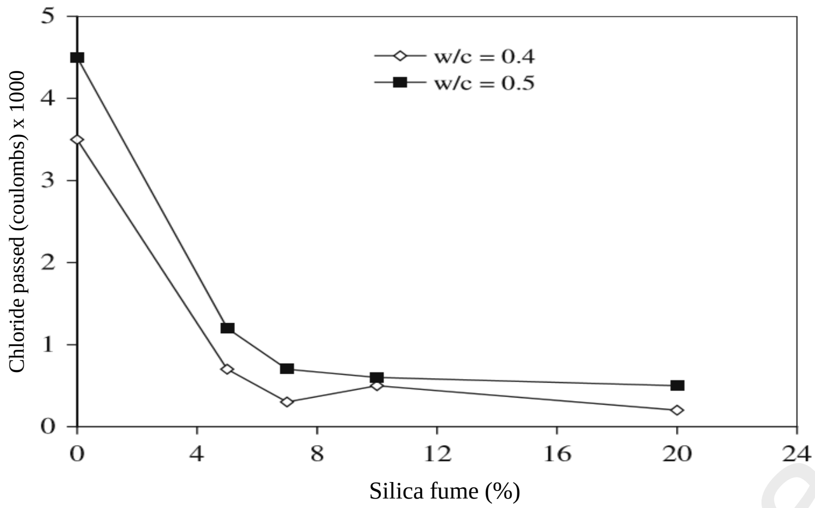


Figure 2.4: Changes in chloride ion permeability of concrete with amount of SF replacement (Perraton et al., 1988)

2.3.2 Fly Ash (FA)

Fly ash (FA) also called pulverized FA, is produced as a result of burning the crushed coal in electric power generating plants. The particles size of FA depends on the type of the equipment used for dust collection. Generally, it is finer than Portland cement, the diameter of FA particles ranges from 1 to 150 µm. The FA chemical composition depends on the source of the coal being burned, the components of FA vary considerably, but all FA includes substantial amounts of silicon dioxide (SiO_2), calcium oxide (CaO) and aluminum oxide (Al_2O_3) (Wongkeo et al., 2014). The pozzolanic activity of FA is determined by its particle size distribution; specific surface; calcium content; and fineness (Jiang et al., 2004). When FA is added to concrete, the CH released during the hydration of OPC reacts with the pozzolanic compounds presented in FA. The products of the pozzolanic reaction are mostly of similar type and characteristics with the cement hydration products. This culminate in availability of additional cementitious products, which improve strength in concrete (Felekoğlu et al., 2006).

FA in cement concrete can significantly improves the cement paste quality and the micro-structure of the transition zone between the aggregate and binder matrix due to its fineness as well as pozzolanic reactivity. As a result of continuous pore refinement due to the addition of FA hydration products in concrete, an improvement in development of strength with curing age is realized (Lo and Cui, 2004). Swamy and Mahmud (1986) stated that concrete comprising 50% of FA as partial substitution for cement developed a compressive strength of 20-30 MPa at the age of 3 days and 60 MPa at 28 days. Siddique (2003) investigated the influence of partial substitution of fine aggregate with various percentages of Class F FA on the compressive strength of concrete up to 365 days. Fine aggregate (sand) was substituted with five replacement levels (10, 20, 30, 40 and 50%) of Class F FA by weight. The results of the compressive strength are presented in Figure 2.5. Based on the results, the following conclusions were drawn: the compressive strength of fine aggregate that substituted the FA concrete specimen is higher than the control concrete for all the ages. The differential of the strength between the FA concrete and control concrete was clearer after 28 days; the compressive strength increased continuously with age for all FA substitute levels; the highest compressive strength was obtained with 50% FA content for all the ages. The compressive strength of 50% FA concrete was 40, 51.4 and 54.8MPa at 28, 91, and 365 days, respectively; and of the observations from this study indicates that Class-F FA could be used appropriately in structural concrete. Yuan and Cook (1983) stated that FA concrete comprising of 30 and 50% FA showed more shrinkage than either the concrete with 20% FA or control concrete, as presented in Figure 2.6. Naik et al. (1994) assessed the effect of incorporation of large quantity (50 and 70% cement substitution) of Class C FA on the permeability of chloride in the concrete. The concrete mixes were labeled as C-3 (0% FA), P4-7 (50% FA) and P4-8 (70% FA). The results of the chloride permeability are presented in Figure 2.7. The permeability of chloride decreases with age. At 2 months, the whole concrete mixes except the 70% FA mixture shows reasonable (2,000 - 4,000 C) permeability in according to ASTM C1202 specifications. The 50% FA concrete blend exhibited lower permeability compared with the control concrete at all ages. The 70% FA sample also exhibit better performance than that of the control concrete at the end of 3 months.

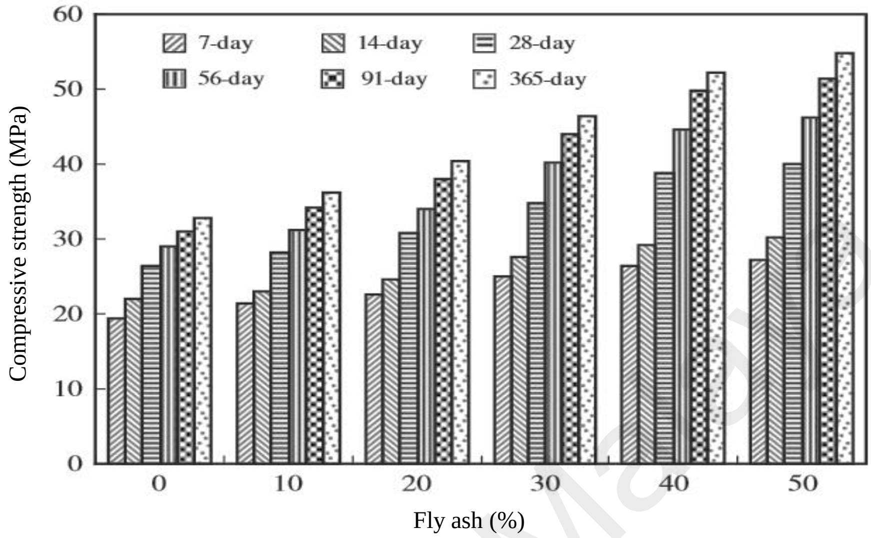


Figure 2.5: Compressive strength vs. fly ash content (Siddique, 2003)

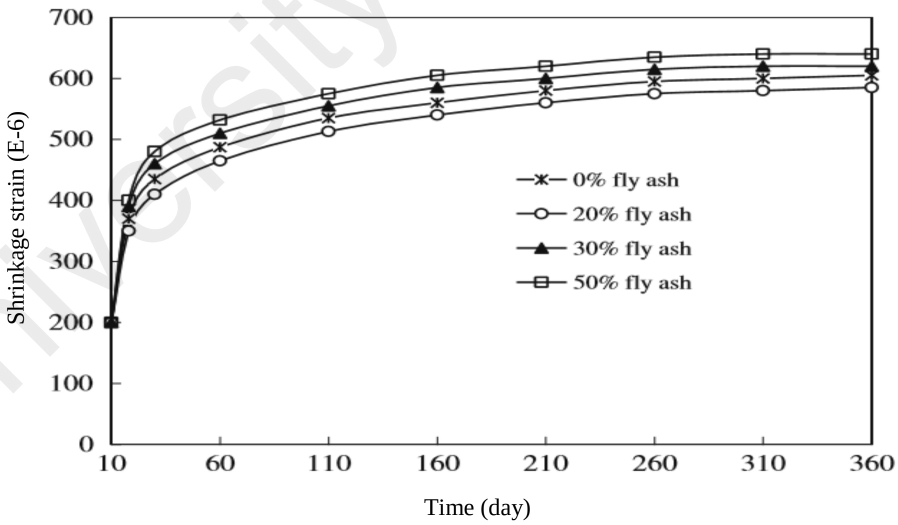


Figure 2.6: Effect of fly ash addition on drying shrinkage of concrete (Yuan et al., 1983)

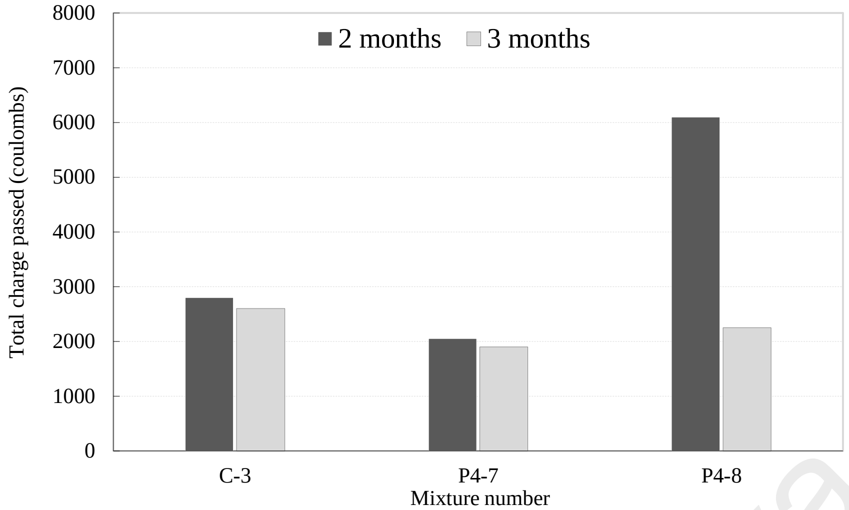


Figure 2.7: Effect of fly ash addition on chloride permeability of concrete (Naik et al., 1994)

2.3.3 Palm Oil Fuel Ash (POFA)

Palm oil fuel ash (POFA) is one of the agro-waste ashes whose chemical composition has a huge amount of silica with a high potential for utilization as a cement replacement (Tangchirapat et al., 2007). High quantities of POFA is generated in Malaysian palm oil mills as a waste with no profitable return. Several studies were conducted to examine the feasibility of using POFA as SCM in concrete, it was reported that the usage of POFA as SCM can enhance several hardened concrete properties (Chindaprasirt et al., 2007; Sata et al., 2007). The reaction of SiO from POFA and the CH from the hydration of cement generates extra calcium silicate hydrate (C-S-H) that helps to improve the strength and durability of concrete (Sata et al., 2007). However, it was suggested that POFA cannot be used to replace cement more than 10% by weight of binder. Tangchirapat et al. (2007) stated that POFA has low pozzolanic properties due to its large particle size and porosity, and thus resulting in a very low pozzolanic reaction rate. Therefore, some researchers had to grind POFA by Los Angeles machine using steel ball and mild steel bar to reduce the particle size of POFA. Both methods were suitable for the particle size reduction of POFA to finer material than OPC. Thus, the finer POFA helps to improve the strength because of its micro filling property. Chindaprasirt et al. (2007) reported that the compressive strength of concrete comprising POFA is greater than that of OPC concrete. This is mainly attributed to the good pozzolanic properties of the finer POFA. Incorporation of POFA reduces the demand for cement in construction industry, thereby reducing the cost of production of cement and decreases the environment pollution resulting from cement factories. Therefore, not only does POFA enhance concrete properties, but also provide significant environmental and economic benefits.

2.3.4 Ground Granulated Blast Furnace Slag (GGBS)

Ground granulated blast furnace slag (GGBS) is a by-product of iron production in a blast furnace, where coke, limestone and iron ore are raised to a temperature of 1500◦C (Babu and Kumar, 2000). When these materials are processed in the blast furnace, two different products are formed: molten slag, and molten iron. The molten slag is lighter and floats over the molten iron. The molten slag mainly contains alumina and silicates from the main iron ore, together with certain oxides from the limestone. Babu et al. (2000) investigated the cementitious efficiency of GGBS in concrete at different replacement levels (10-80%). The results revealed that 28-day compressive strength of concretes contains GGBS up to 30% were all slightly more than that of control concretes, while at the other replacement percentages of more than 30% GGBS, the strength was lower than that of control concrete. Basheer et al. (2002) reported that GGBS can be utilized commendably in concrete production as filler material to reduce the pore size, a denser structure can be obtained with a higher percentage replacement of GGBS. Cheng et al. (2005) investigated the effect of incorporating GGBS in concrete towards the water permeability and the resistance against chloride-ion penetration. A concrete of water-binder ratio of 0.55 with 40 and 60% substitution levels of GGBS were tested for chloride-ion penetration test (RCPT) and water absorption. The results revealed that higher GGBS contents produce a denser structure and prevent water penetration in concrete; and the RCPT results show that the maximum total charge-passed was observed in the control concrete specimen and the minimum total charge passed was observed in the mix of 60% GGBS specimen, which considered the maximum resistance to chloride-ion penetration.

2.4 Lightweight Aggregate

As from the late nineteenth century, lightweight aggregate (LWA) are used in construction to substitute the normal weight aggregate (NWA). Application of LWA in structural concrete reduces the production cost of construction (Qiao et al., 2008). The decline in natural resources nowadays leads to the development of different types of man-made LWA. LWA has its own advantage when used in the production of LWC. The most popular way of achieving LWC production is by using LWA, which can be used for either whole or partial substitution of conventional aggregates (CA) (Polat et al., 2010). The particle density of the aggregate is the ratio between the mass of certain quantity of aggregate and the volume of all individual particles of the quantity. The volume includes the voids within the particles but does not include the space between the particles. The particle density is a function of both the specific density of the material and the void content of the particles. LWA have a density significantly lower than conventional aggregate, ranging from 560 to 1120 kg/m^3 (Chen et al., 1999).

The quantity of water absorbed by aggregate mainly depends on the pore structure and the condition of the surface (Lo and Cui, 2004). Some LWAs contain pores of microscopic dimensions while others have pores up to several millimeters (Bentur et al., 2001). Though, there are various type of LWA, they can be generally categorized into two groups; natural, which include oil palm shell, scoria, diatomite, sawdust, volcanic cinders, bottom ash and pumice; and, artificial, which include vermiculite, expanded clay, slag, shall, slate and perlite (Alshihri et al., 2009; Hossain et al., 2011). Kılıç et al. (2003) reported that main reason for using LWA in construction is to reduce the self-weight from concrete, which allows engineers to design slenderer structural element such as column and foundation that could offer similar strength to normal weight concrete. Generally, stiffness of LWC is less compared to NWC (Zhang and Poon, 2015). The properties of fresh concrete are affected by the water absorption of porous LWA (Hwang and Hung, 2005). The effect of poor curing on porous lightweight concrete aggregate is minimal as compared to conventional concrete aggregates. This condition is a result of the additional water absorbed and internally stored in the LWA. Thus, hardened concrete benefits from the water absorption capacity of the POC (Al-Khaiat and Haque, 1998). However, the absorption of LWA is an important factor as the partially or unsaturated aggregate will influence the fresh and hardened concrete properties such as workability, density and thermal insulation (Kan and Demirboğa, 2009).

2.5 High Performance Concrete (HPC)

Forster (1994) defines high-performance concrete (HPC) as concrete made with the appropriate materials according to a selected design, when properly mixed, consolidated and cured, the resulting concrete will be of excellent performance. The main distinction between high-strength concrete (HSC) and high-performance concrete is the mandatory requirement of high durability in the case of HPC. Johari et al. (2012) stated that HPC could be produced from a wide variety of mix configurations, but for greater strength level, particularly for 28 days' strength ranging from 62 to138 MPa. The amount of cement used in production of HSC ranges from 400 to 550 kg/m^3 (Alonzo et al., 1993). Nowadays, HPC in term of strength is taken as a compressive strength in excess of 80 MPa or 12000 psi (Aıtcin, 2003). The use of concrete admixtures also contributes to improvement of concrete properties including durability. HSC has a cement matrix with low capillary pores, which could be as a result of reduction in w/c ratio and usage of high range water reduction as well as usage of powder materials to increase the amount of products of hydration (Sobolev, 2004). Two main factors are crucial for achieving HSC. Firstly, the densification of matrix and transition zone between the matrix and aggregate must be high. High densification of matrix and transition zone can be achieved by reducing w/b ratio and the use of pozzolanic materials to consume more Ca $(OH)_2$ and produce more C-S-H as well as achieving high packing for matrix, thereby producing HSC (Hassan et al., 2000). Secondly, the utilization of various types of coarse material such as limestone aggregate improves the transition zone due to the chemical action of calcium carbonates. Moreover, the use of crushed aggregate with small maximum size provides a large surface area leading to an increase in the transition zone. (Aıtcin, 2003). To obtain concrete with a high strength, the water to binder material ratio (w/b) is kept low, usually below 0.35 (Rashid and Mansur, 2009). To provide a mixture with sufficient workability, usage of superplasticizer is mandatory. The low w/b ratio reduces the porosity of concrete, hence produces a dense microstructure, which enables HSC to act as a true composite material where aggregate are no longer considered as inert fillers, but rather as active components whose mineralogy, strength and elastic properties significantly influence the ultimate strength and elastic modulus of concrete (Baalbaki et al., 1991).

2.5.1 Pozzolanic Materials

Mineral admixtures are powders, which are used to improve the characteristics of concrete. They are also called cement replacement materials or pozzolans that generally uses at least 5 to 15% by mass of the total cementitious materials. ASTM C 618 describes pozzolanic materials as those that contains silica or silica and alumina material as its major composition. Moosberg-Bustnes et al. (2004) reported that the physical effect of powders on the concrete properties occurs as a result of infusion of the fillers into void between cement particles. This lead to improve the concrete properties in fresh and hardened state. The physical properties of powder like fineness, shape and particle size distribution should be considered in the mix design. In case the surface area of cement is less than that of the powder, there will be increase in water demand to maintain the same workability. Felekoğlu et al. (2006) stated that the optimum quantity of cementitious materials depends on their physico-chemical and physical characteristics, which have a significant effect on the fresh paste properties. These characteristics assume the particle size distribution, fineness fraction content, surface porosity and shape of particles. It is occasionally hard to recognize them amongst the effects of these factors because of the complex effect of combining these factors (Rashid et al., 2009). The effect of chemical reaction when the filler reacts with certain constituents of the cement to form a cement gel. For instance, pozzolanic materials such as metakaolin, SF and FA react with $Ca(OH)_2$ to produce C-S-H, which contributes to develop the strength. Pozzolans have no intrinsic binding properties and their latent potential must be developed through combination with Portland cement. They react with lime liberated from cement hydration to form calcium silicate hydrates that gives Portland cement its binding property (Cwirzen and Penttala, 2005).

2.5.2 Effect of Aggregates

The aggregate should be chosen by considering the performance of fresh and hardened concrete. Aggregates gathered on the 4.75mm (No.4) sieve are deemed coarse aggregate (ASTM C125, 2004). Amparano et al. (2000) found that a boosted with a rise in the content of the coarse aggregate decreases the workability of concrete mix thereby reducing the strength. Suwanvitaya et al. (2006) stated that the total aggregate content had a varying effects on the compressive as well as splitting tensile strength, decreasing strength at lower aggregate content and raising at the higher ranges. Baalbaki et al. (1992) showed that the elastic modulus of concrete was affected by the volume fraction and elastic properties of aggregates. The elastic modulus of cement-based composite with the rising volume fraction of the aggregate. Aggregates also have a significant influence on the properties of hardened concrete (Cho et al., 2000). The deformation properties of concrete are particular affected by aggregate due to a combination of the effects, including volume concentration water demand, aggregate stiffness and paste/aggregate interaction

(Alexander, 1996) . Meddah et al. (2010) reported that HSC can be obtained by using coarse aggregate with maximum size range of 5-14mm, although some of researchers observed that the size range of 10 to 12mm were preferable. However, the type of aggregate also has a significant role in producing HSC (Beshr et al., 2003). Khaleel et al. (2011) concluded that the shape and size of coarse particles have a substantial effect on the mortar and paste content. Normally rounded river gravel requires lesser paste or mortar, while limestone and granite need the highest volume of mortar. Crushed aggregate can enhance the strength due to the interlocking of the angular particles, however reduced the workability (Halicka et al., 2013).

2.5.3 High Range Water Reduction (HRWR)

High-range water reducers prevent the formation of cement-water agglomeration in concrete mixture and disperse the cement particle in aqueous phase (Cheung et al., 2011). Therefore, Superplasticizer can increase the strength by lowering the quantity of mixing of water and increasing the flowing ability (Aitcin, 1995). Superplasticizer (SP) contribute to achieve denser packing and lower porosity of concrete, and thus assisting in producing high strength and good durability concrete (Abd Elrahman and Hillemeier, 2014; Shi et al., 2015). SP has a big influence on the fresh and hardened concrete properties especially in high performance and ultra high performance concrete. It is an essential material that must be used in the production of high strength and high-performance concrete. The selection of the type of superplasticizer and its dosage have a significant effect on the concrete in both fresh and hardened states (Boukendakdji et al., 2012).

2.5.4 Curing of High Performance Concrete

Concrete properties and durability are significantly influenced by curing, it greatly affects the hydration of cement. High-performance concrete with extremely low water to binder (w/b) ratio is often characterized by high cracking sensitivity. The lack of moisture in cement paste can resulted dry shrinkage due to self-desiccation that may aggravate the durability problems (Zhutovsky et al., 2004). A proper curing is crucial to produce greater hydration products, and to reduce the porosity and drying shrinkage cracking of concrete, and thus achieving high strength and greater resistance to the physical and chemical attacks in aggressive environment. New curing method was proposed based on incorporation of pre-soaked LWA into the mix, which acts as an internal water reservoir preventing reduction of relative humidity (Zhutovsky et al., 2004). Past studies demonstrated that this kind of curing could be successfully applied to obtain improved HPC (Bentur et al., 2001; Kohno et al., 1999). The amount of moisture in LWA varies, depending on storage and pre-wetting (Kohno et al., 1999). Bentur et al. (2001) reported that the concrete with saturated LWA exhibited no autogenous shrinkage, whereas the NWC with the same matrix exhibited large shrinkage with no effect on strength. Suzuki et al. (2009) investigated the efficiency of internal wet curing using waste porous ceramic coarse aggregates. They reported that the waste recycled porous ceramic aggregate has a great potential for internal wet curing purposes and can be used successfully in HPC mixtures to significantly mitigate autogenous shrinkage.

2.6 Sustainability in Construction Industry

Generation of large amounts of waste materials and their discarding are some of the great issues confronted by present day civilization. Disposal of waste material is becoming a severe environmental challenge in several mega towns all over the world (Akadiri et al., 2013). A lots of this waste are generated from construction industry, leading to a major effect on the environment (Richardson et al., 2010). One of the major aim of modern day scientists is continuous production of sophisticated concrete, regarding completely environmentally benign technical parameters. The possible tools and strategies necessary to solve the environmental challenges in the concrete and construction industry could be realized in different ways (Grabiec et al., 2015).

2.6.1 Construction Materials

Construction industry is one of the biggest businesses in the world. Currently, there is an enormous increase in the speed of development of these industries worldwide specifically in the developing countries due to the rapid industrial and economic developments and the consequent of infrastructural development (Mateus et al., 2013). Reducing the environmental effect of concrete structure to the barest minimum without compromising on their performance is one of the most important concerns towards sustainable development in concrete industry (Khokhar et al., 2010). To assess the influence of construction materials on the environment, several issues must to be considered. These include collection, treatment and production of raw materials, construction, service life, demolition and discarding. Material efficiency is of utmost significance towards production of construction materials that are sustainable. Correct material selection by considering their complete service lifetime and selecting products with minimal environmental effects could minimize CO_2 emissions by up to 30% (González et al., 2006). Other factors that significantly influence the select of construction materials are their social and costs demands including health effect, good mechanical properties i.e. strength and durability, and the capability to build fast. Ideally, combining all the social, economic and environmental factors can give a clear description of a material thereby helping in the process of decision-making concerning selection of suitable materials for buildings (Abeysundara et al., 2009). Akadiri et al. (2013) stated that the materials that minimize resources usage, minimize the environmental impacts could be considered as sustainable construction materials. Thus, by considering the environmental impact of the construction industry, it is crucial to produce construction materials that are sustainable with increase in service life and least future maintenance requirements.

2.6.2 Concrete Production

Concrete is the main construction material and plays an important role in the development of present civilization. According to Meyer (2009), the consumption of concrete as a construction material worldwide is more than twice the total usage of all other construction materials such as steel, wood, aluminum and plastic. The overall yearly production of concrete worldwide is over 10 billion tones, which is greater than 0.6, 5 and 0.9 billion tons of potable water, aggregate and Portland cement, respectively required for the production of such quantity of concrete (Meyer, 2009). The considerable usage of concrete as a building material is due to its flexible properties including strength, raw materials abundance, affordability and durability which make the concrete the most attractive for most building purposes. Nevertheless, production of concrete has several of adverse effects on the environment, including CO_2 and other greenhouse gases emission and the use of non-renewable natural materials such as natural stone. Approximately 5% of global CO_2 emissions originate from the manufacturing of cement, the third largest source of carbon emission in the United States (Huntzinger and Eatmon, 2009). In addition to the generation of CO_2 the cement manufacturing process produces millions of tons of the waste product cement kiln dust (CKD) each year contributing to respiratory and pollution health risks (Huntzinger et al., 2009). CKD is a potential hazardous waste, in part because of the caustic nature and its potential to be a skin, eye, and respiratory irritant. Therefore, recently immense attention has been directed towards dealing with the environmental concerns regarding their usage in the production of concrete (Mateus et al., 2013).

Concrete contains several constituents, making the environmental impact in the production of concrete a difficult mechanism partially governed by the individual effects from each of the components and partially governed by the combined effect of the components when they are mixed together. Thus, the sustainability issue associated with production of concrete needs to be addressed by considering their individual and combined effects of the components (Khaloo et al., 2008). Conversely, enhancement of mechanical properties, design of concrete, service life and durability should also be given a serious consideration since these factors also influence the environmental impact of concrete(Rao et al., 2007). Concrete generally contains at least three components: cement as a binder, aggregates which usually account for 70-75% by volume of the concrete and water. Each concrete constituent has its own environmental impact. Meanwhile, the sustainability of concrete as a construction material is intensely affected by the aggregate and cement industries (Rosković et al., 2005).

2.6.3 Aggregate Industry

Aggregates normally constitute 70-75% by volume of the concrete. Therefore, they play a significant role in the properties of concrete like workability, strength and durability. Conventional concrete comprises of gravel in different shapes and sizes as coarse aggregate and sand as fine aggregate. Aggregates are the best richly utilized materials since it is the main constituents of concrete (Meador and Layher, 1998). Both coarse and fine fractions of the aggregates are normally obtained by mining. Rock and mined aggregates are collected via several means including dredging and blasting. Aggregates can be utilized directly as produced with respect to size naturally by weathering or crushing of large stone (Ayenagbo et al., 2011). By comparing with the environmental impact from production of cement, aggregate production or mining has a minute impact since only simple extraction with no fundamental modification of material is essential in production of aggregates. Nevertheless, in recent times, the mining of rock and aggregates is becoming a normal challenge in most parts of the world since the demand for gravel and sand increases rapidly due to the infrastructure activities worldwide (Rao et al., 2007). However, this problem can be solved by proper planning and policy implementation. Therefore, the production of concrete using waste materials as aggregates is a good option towards meeting the sustainability goals in production of concrete.

2.6.3.1 Waste Materials as Aggregate in Concrete

Aggregate plays the largest constituent of concrete volume and thus play a significant role in most properties of concrete including workability, strength, and durability. In recent times, a number of waste materials were investigated to be used as aggregates in concrete production. Substantial research was carried out on utilization of several materials as aggregate replacement including coal ash, sintered sludge pellet, blast furnace slag, rubber waste, waste plastics, and others. This type of waste material application can solve challenges of inadequate aggregate in several construction sites and minimize environmental impacts concerning waste disposal and aggregate mining (Meddah and Bencheikh, 2009). Utilization of waste materials as aggregates can also reduce the cost of concrete production. Jepsen et al. (2001) stated that the utilization of industrial wastes in the concrete production could lead to sustainable design of concrete and greener environment. Development of concrete with non-conventional aggregates is urgently required for economic as well as environmental reasons. The waste generated in the ceramic industry have been used by Senthamarai et al. (2005) as coarse aggregate in the production of normal concrete. They reported that waste from ceramic industry can be used in the production of concrete due to its several favorable properties and the resemblance with natural crushed stone aggregate. Waste generated from demolition of construction can be used to produce recycled aggregate in construction. Meyer (2009) reported that most of the strength reduction in concrete made from recycled coarse aggregate ranged from 5 to 24 %, compared to the conventional concrete. Sagoe-Crentsil et al. (2002) stated that the density of recycled concrete aggregate is lower than that of normal aggregate concrete because of the formation of porous residual mortar lumps inside the demolished material. Using water treatment sludge as LWA has the ability to produce concrete with satisfactory compressive strength and splitting tensile strength properties (Huang and Wang, 2013). Yoon et al. (2003) reported that using sea shells as a partial aggregate substitute is more viable and could also be beneficial for construction industry, by producing a renewable and cheaper aggregate material to withstand the growing demand for construction industry. Ohimain et al. (2009) mentioned that the inadequate construction materials in Nigeria, specifically the main constituents of aggregate, have compelled a number of coastline communities to use waste shells aggregate as an essential material for the construction purpose. Dahunsi (2004) reported that full aggregate replacement of periwinkle shells is not feasible. The shells can only be used as partial substitution for conventional aggregate in normal construction purpose. The use of waste plastic as LWA for LWC production has gained much attention from researchers. This method provides both production of a LWC and recycling of the plastic waste in an economical way (Koide et al., 2002). Khaloo et al. (2008) investigated the use of tyre chips as an aggregate of up to 50% replacement of the total aggregate of the design mix. The results revealed that 25% is the optimal aggregate substitution, which gives the best strength.

2.7 Palm Oil Industry

Oil palm milling is the process of extracting oil palm from fresh fruit bunches (FFBs) and producing crude palm oil and palm kernels (Ahmad et al., 2007) . Malaysia is one of the primary producers of palm oil in Asia. It is the second largest palm oil production in the world, producing more than half of world’s palm oil annually (Teo et al., 2007). Recently, the palm trees plantation in Malaysia are continuously increasing due to Malaysian government strategies for palm oil-based biodiesel production (Hosseini and Wahid, 2012). Malaysian Palm Oil Board (MPOB) reported that the land area committed to oil palm plantation in 2012 accounted for around 5,076,929 ha. Table 2.4 depicts oil palm planted areas in different states of Malaysia at the end of 2012. Generally, palm trees are planted in Malaysia for food applications like frying oil and cooking oil. Palm trees usually have a vertical trunk and feathery leaves and every year around 20–40 new leaves known as palm frond are grown. Bunches of palm fruit develop between trunk and base of the new fronds as shown in Figure 2.8. Generally, 5-6 years after plantation the first crop of fresh fruits can be harvested and each tree can provide palm fruit for 25–30 years (Hosseini and Wahid, 2014). The weight of fresh fruit is around 10 to 40 kg. Each fruit has a spherical shape and a black color before turning to orange–red when ripe (Hosseini and Wahid, 2014). Indeed, the rate of FFB produced per hectare in different states of Malaysia in 2010 are demonstrated in Figure 2.9.

Table 2.4: Oil palm planted area in different states of Malaysia (Hosseini and Wahid, 2014)

State	Mature	%	Immature	%	Total	%
Johor	618,353	89.59	95,777	13.41	714,130	14.07
Kedah	76,181	90.13	8,342	9.87	84,523	1.66
Kelantan	91,182	66.23	46,497	33.77	137,679	2.71
Malacca	48,718	92.75	3,806	7.25	52,524	1.03
Negeri Sembilan	143,580	85.94	23,496	14.06	167,076	3.29
Pahang	595,799	85.09	104,402	14.91	700,201	13.79
Perak	338,100	88.99	41,846	11.01	379,946	7.48
Perlis	197	69.37	87	30.63	284	0.01
Penang	13,264	97.85	292	2.15	13,556	0.27
Selangor	124,080	90.77	12,611	9.23	136,691	2.69
Terengganu	136,509	79.6	34,984	20.4	171,493	3.39
Sabah	1,292,757	89.61	149,831	10.39	1,442,588	28.41
Sarawak	874,152	81.22	202,086	18.78	1,076,238	21.2
Total	4,352,872	85.45	724,057	14.55	5,076,929	100

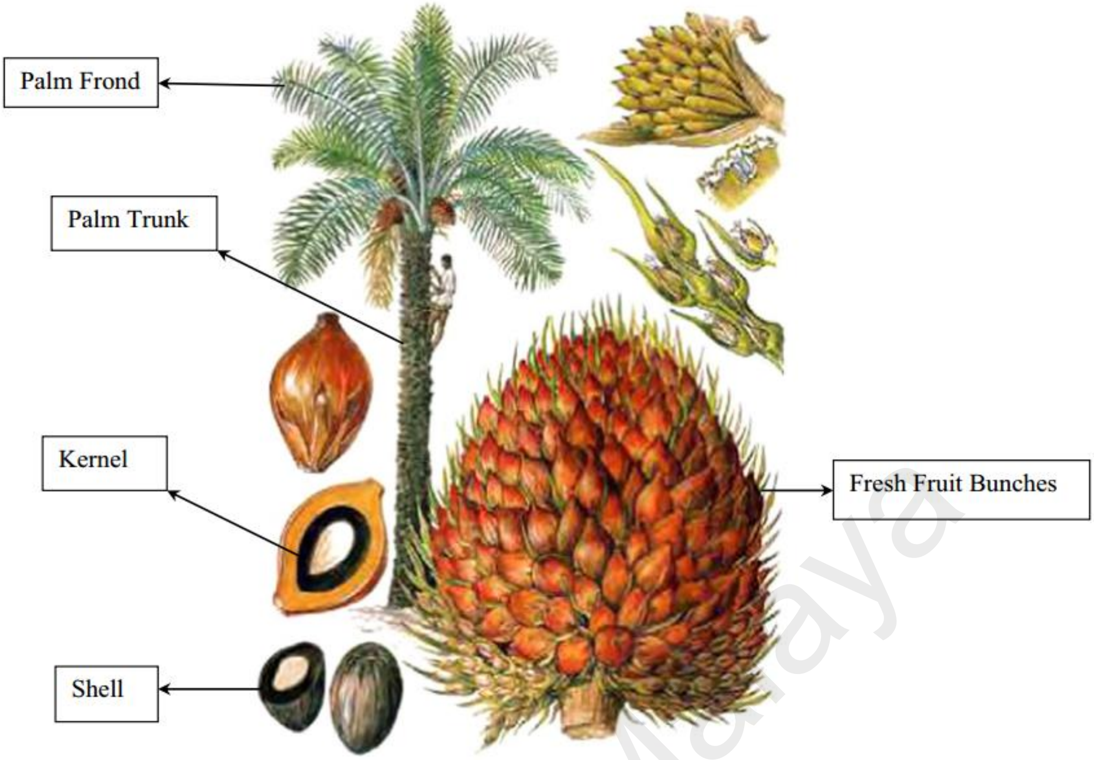


Figure 2.8: A typical palm tree and FFB (Hosseini and Wahid, 2014)

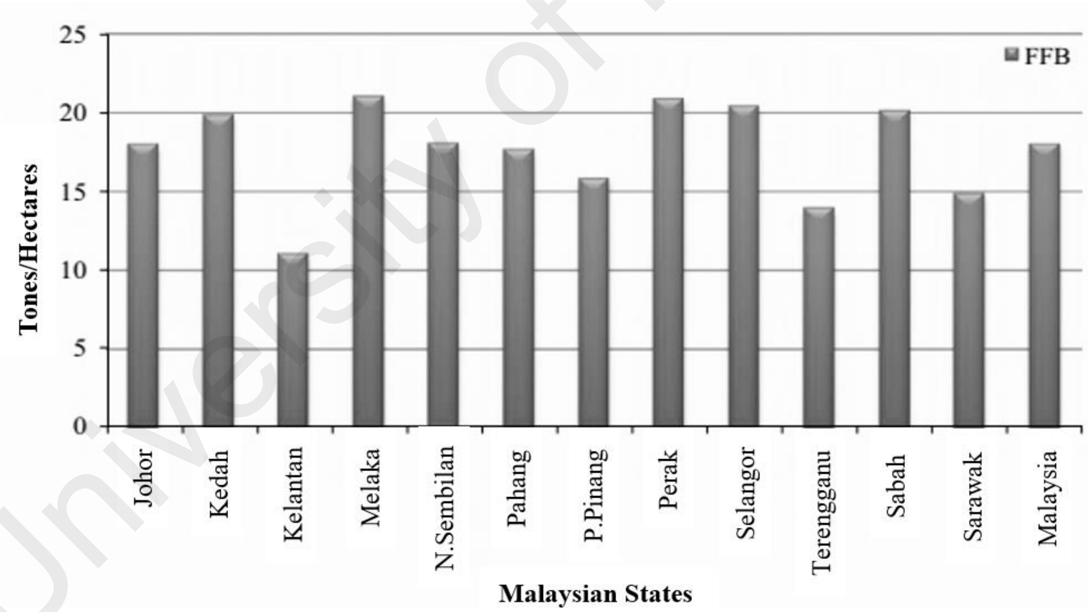


Figure 2.9: The rate of produced FFB in different states of Malaysia in 2010 (Hosseini and Wahid, 2014)

2.8 Palm Oil Mill Waste

Palm oil industry is a major contributor to the pollution problem occurring in Malaysia, with an estimated 2.6 million tons of solid waste produced annually (Tangchirapat et al., 2007). These wastes have been projected to grow because of the ongoing global consumption demand for palm oil. The high amount of waste generated from the palm oil industry is mostly composed of palm oil clinker (POC) and oil palm shell (OPS) (Basri et al., 1999). Additionally, the waste also includes POFA and empty fruit bunches (EFB) (Tangchirapat et al., 2007). Figure 2.10 shows the types and quantity of different by-products and solid waste generated from palm oil industry in Malaysia in million tons annually. Figure 2.11 illustrates the summary of biomass byproduct generation in palm oil industries in Malaysia. Figure 2.12 shows the solid waste of local palm oil mill.

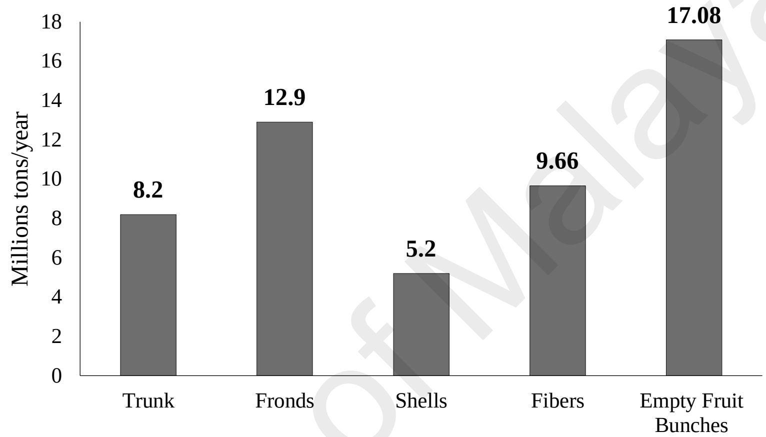


Figure 2.10: Oil palm bio products in Malaysia (Hosseini and Wahid, 2014)

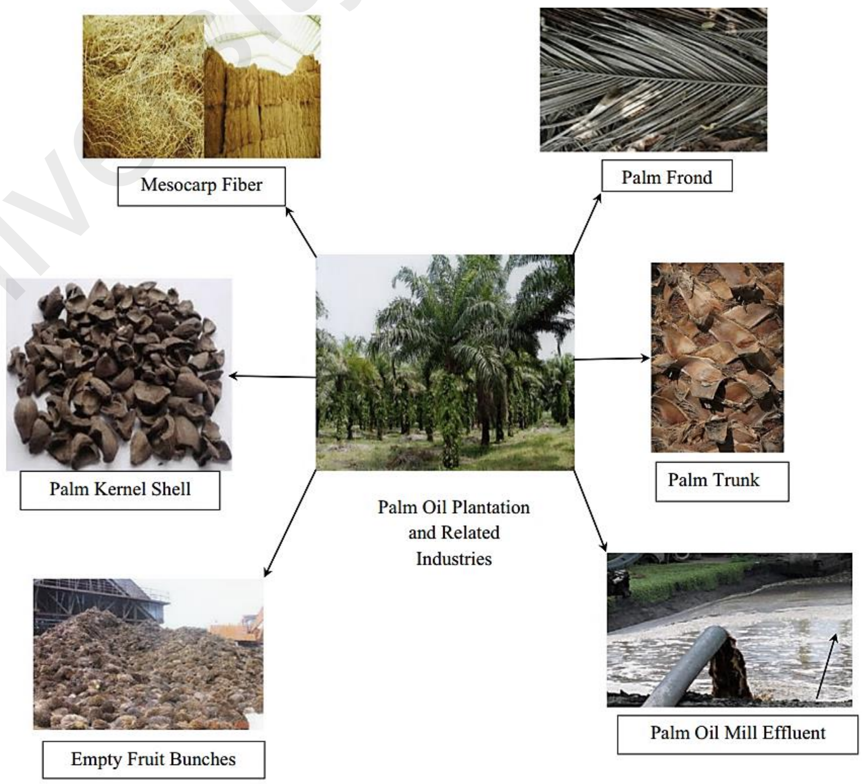


Figure 2.11: Biomass byproducts generation in Malaysian palm oil industry (Hosseini and Wahid, 2014)

Figure 2.12: Solid waste of palm oil mill (Taken by author)

2.8.1 Oil Palm Shell (OPS)

Oil palm shell (OPS) is an agricultural waste material from palm oil industry. It is light and naturally sized suitable as coarse aggregate for the manufacturing of lightweight concrete (Basri et al., 1999). The use of agricultural wastes as a substitute for aggregate material in concrete has an economic advantage and engineering potential (Mannan et al., 2004) . Concrete comprising of agricultural wastes abundant in an agro-based country like Malaysia gives a remarkable alternative to the conventional lightweight concrete (Okafor, 1988). Previously, researchers have used OPS as a lightweight substitute for traditional aggregates for concrete production (Jumaat et al., 2009; Mannan et al., 2006; Teo et al., 2010; Teo et al., 2007). OPS concrete can be utilized in lightweight concrete applications that involve low to moderate strength (Mannan et al., 2004). OPS concrete also could be used in countries and nearby areas where palm oil factories are located for houses, road-kerbs, drain block, etc., which might reduce the cost of concrete (Teo et al., 2007). Mannan et al. (2004) reported that concrete containing OPS coarse aggregate can be used for several purposes including pavement of road, flooring of buildings and concrete drains. Basri et al. (1999) investigated the effect of using OPS as coarse aggregate and FA as partial cement replacement in concrete in different curing methods. They reported that OPS concrete has a compressive strength of 40–55% lower than that of control concrete as shown in Figure 2.13. The maximum compressive strength was observed in concrete subjected to standard humid curing settings. The strength decrease was mostly due to the weaker crushing strength of OPS aggregates as compared with that of normal aggregate. However, these results were still in the typical range of SLWC. Mannan and Ganapathy (2002) stated that concrete containing OPS aggregates has lower compressive strength, dynamic elastic modulus, flexural and splitting tensile strengths than control concrete. However, the strength properties of OPS concrete meet the required standard for SLWC. Teo et al. (2010) reported that OPS concrete had higher drying shrinkage as compared with the control concrete. However, the increase was in the normal range of LWC. The results also revealed that the water absorption of OPS concrete was also greater compared to that of control concrete due to the higher pore structure of the OPS aggregates concrete. Teo et al. (2010) stated that the results revealed the same permeability (water and chloride) of concrete with OPS aggregates as other LWA concrete. OPS concrete showed moderate to high chloride-ion penetrability, the values ranged from 3581 to 4549 Coulombs.

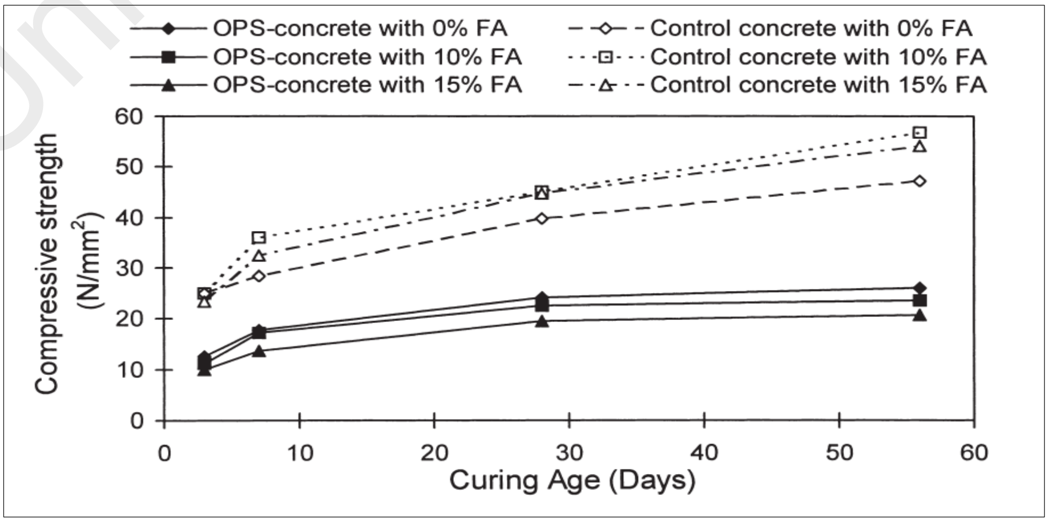


Figure 2.13: Development of compressive strength (Basri et al., 1999)

2.8.2 Palm Oil Clinker (POC)

POC is a by-product resulting from palm oil shell incineration in the form of light solid fibrous material. The large chunk of POC is grey in colour and has the appearance of porous stone, flaky, irregularly-shaped, with rough and sharp broken edges as shown in Figure 2.14. POC is abundant and have small commercial value in Malaysia; hence, this industrial waste can be converted into potential construction materials. Attempts have been made to utilize these materials as aggregate in concrete production (Roslli et al., 2002). POC is lightweight solid material when crushed possesses the potential as aggregate for concrete production. The use of agricultural wastes as an aggregate or cement replacement material in concrete has engineering potentials and economic advantages. Each type of agricultural waste has physical and chemical properties that are suitable for proper application in concrete (Mannan et al., 2010). Kanadasan et al. (2015b) reported that the similarity of the particle size distribution and the grading features of the sand and POC fine aggregate indicate the suitability of POC fine substitution in concrete production. OPS and oil-palm-boiler clinker (OPBC) are used as an alternative LWA in tropical regimes and countries that have a palm oil industry (Bashar S Mohammed et al., 2014). The benefit of using POC as LWA is the reduced dead load of concrete structures without much loss in the strength of the structure. This condition is possible because LWC can reduce the dead load by as much as 35% and still provide the structural strength (Roslli et al., 2002). Abdullahi et al. (2008) studied the trial mix proportions for POC concrete to determine the properties of POC aggregate such as particle size distribution, specific gravity, and water absorption. It was shown that utilization of POC aggregate in the mix design of concrete is possible without any admixture. A previous research by Kanadasan and Abdul Razak (2015a) showed that utilization of POC reduces the cost and energy usage and lowers carbon emission.

Figure 2.14: Raw POC from palm oil mill (Taken by author)

2.8.2.1 Physical properties

According to previous studies presented in Table 2.5, the bulk densities of POC aggregates vary within different ranges. The loose and compacted bulk densities are in the range of (1040-1120) kg/m^3 and (740-860) kg/m^3 for fine and coarse POC aggregate, respectively. The reduction in the bulk densities of POC aggregates are in the range of (35-43%) and (40-45%) lower than normal sand, and conventional coarse aggregates, respectively. However, all the results are within the satisfactory range of 700 to 1400 kg/m3 for the structurer purpose (Aslam et al., 2016). POC aggregate is a porous material and will absorb huge amounts of water compared to the NWA (Bashar et al., 2014). As shown in Table 2.5, the 24-h water absorption are in the range of (4.7 to 26.5%) and (2.7 to 5.4%) for fine and coarse POC aggregate, respectively. The specific gravity of a material is the ratio of the density of that particular material and that of water. It can be seen that POC also has varying values of specific gravity. It was in the range of 1.7 - 2.2 and did not exceed the specific gravity value of NWA.

Table 2.5: Physical properties of POC aggregate (Aslam et al., 2016)

Aggregates	Specific Gravity	loose bulk density (kg/m^3)	Compacted bulk density (kg/m^3)	Moisture content (%)	24h water absorption (%)	References
Fine	1.8	1120	-	-	14.3	(Abdullahi et al., 2008)
Coarse	1.7	790	-	-	5.4	
Fine	2	1120	-	0.11	26.4	(Bashar S. Mohammed et al., 2011)
Coarse	1.8	780	-	0.07	4.4	
Fine	1.97	-	-	0.5 ± 0.25	10 ± 5	(Kanadasan and Abdul Razak, 2015a)
Coarse	1.73	-	-	1 ± 0.5	3 ± 2	
Coarse	1.7	-	800	-	2.7	(Mannan et al., 2010)
Fine	-	-	1080	-	7.5	(Roslli et al., 2002)
Coarse	1.73	-	827	-	3	
Fine	2.2	-	1040	-	-	(Ahmad et al. 2007)
Coarse	1.8	740	860	-	4.6	
Fine	1.7	-	1080	-	-	(Zakaria, 1986)
Coarse	1.95	-	815	-	-	
Coarse	2.2	-	860	0.08	4.6	(Ahmad et al. 2008)
Fine	2.2	-	-	0.5 ± 0.25	10 ± 5	(Kanadasan et al., 2014a)
Coarse	1.7	-	-	1 ± 0.5	3 ± 2	

2.8.2.2 Aggregate Crushing Value

Aggregate crushing value (ACV) gives a relative measure of the resistance of an aggregate to crushing under a gradually applied compressive load. A lower crushing value generally indicates the high capability of the aggregate to sustain load, which indirectly provides good strength achievement in the concrete. Kanadasan et al. (2015a) investigated the variation in ACV of various POC samples collected from 14 different locations in Malaysia. The results are presented in Figure 2.15. Generally, the states with lower ACV gave higher compressive strength results. This relationship could also serve as a potential indicator or estimator of the strength properties for different POC sample. The micro voids available in POC affects the potential of having early crack propagation in concrete or mortar as it may induce a weaker region through connection of voids (Kanadasan et al. 2005a). As a result, these voids may provide some reduction in strength properties when incorporated in concrete.

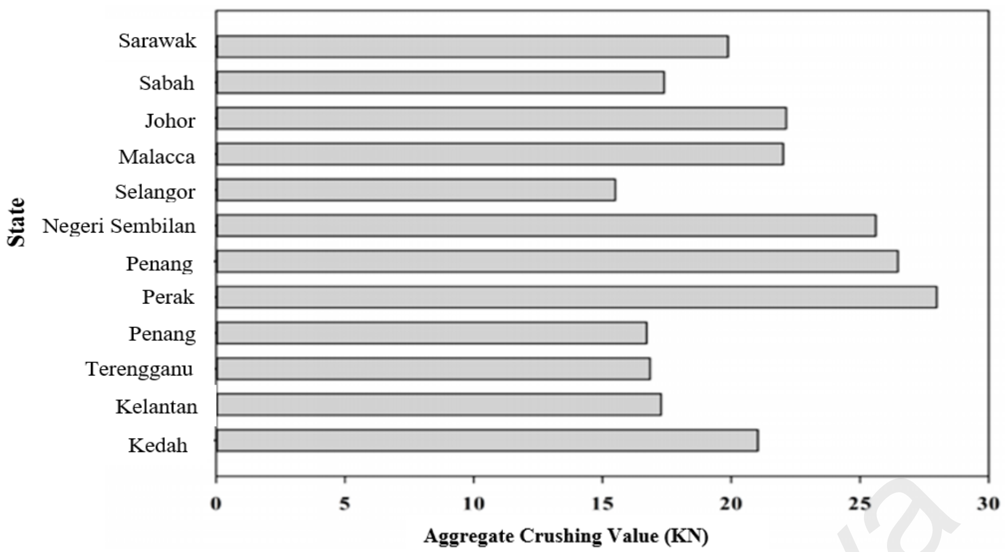


Figure 2.15: ACV of POC for different Malaysian states (Kanadasan et al., 2015a)

2.8.2.3 Microstructural Analysis

Figure 2.16 shows a scanning electron micrograph (SEM) with Energy Dispersive X-ray spectroscopy (EDX) for POC specimen. As observed, the porous nature of POC appears to be eminent at a larger magnification. A large number of voids exist on the surface ranging on average from 1 mm to 500 μm (Kanadasan et al. 2005a). Micro-pores are also observed on the surface of the POC aggregate at 20 μm magnification. The existence of the large number of voids and pores contributes significantly to the light nature of POC aggregates (Kanadasan et al. 2015b). Figure 2.18 depicts the SEM image and EDX results of POC aggregate-cement paste interface. The higher silica (Si) (SPOT 1) and calcium (Ca) (SPOT 2) peaks corresponding to the POC aggregate and cement paste, respectively, indicate the boundary between the aggregate and the cement paste. A packed or dense state of aggregate cement paste interface is evident as a myriad of SCM properties. Higher paste content coupled with enhanced workability improved the aggregate cement paste region to provide a better bond formation. Utilization of POCP as SCM improve significantly the aggregate cement interfacial zone due to its ability to fill the voids and take up the shape of the interacting boundary (Kanadasan et al. 2015b).

This resulted in a high strength sustaining capacity of the mortar even with a higher POCP replacement.

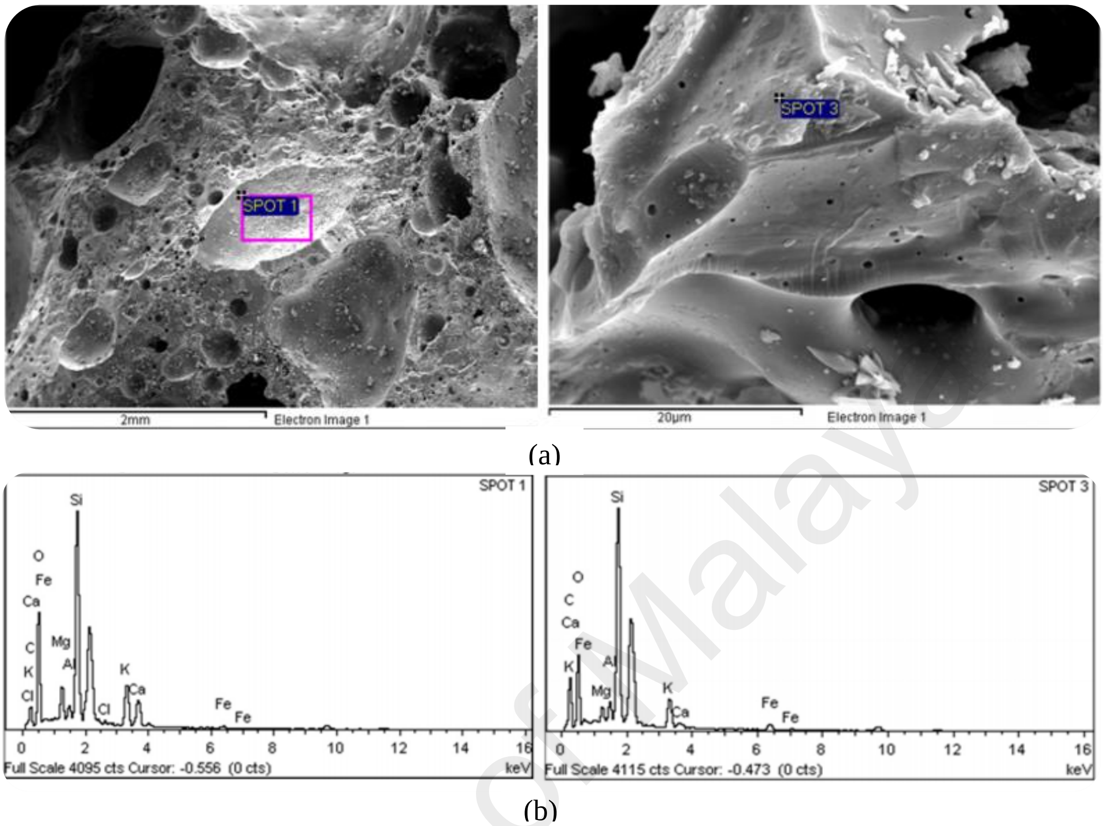


Figure 2.16: POC aggregate: (a) micrograph at a larger magnification; (b) EDX (Kanadasan et al. 2015b)

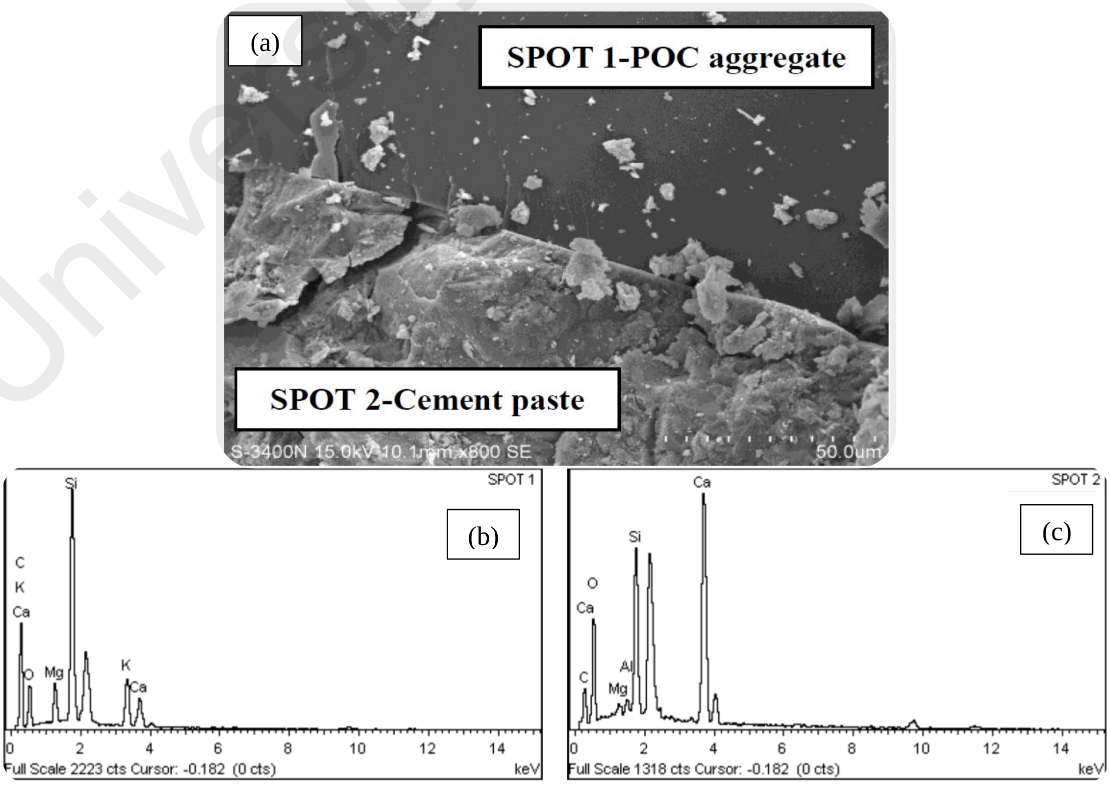


Figure 2.17: (a) POC aggregate - cement paste interface; (b) EDX of POC aggregate-spot 1; (c) EDX of cement paste interface-spot 2 (Jegathish, 2016)

2.8.3 Palm Oil Clinker Powder (POCP)

POCP can be obtained after grinding the moisture free of POC in control ball mill at 150 RPM for 8 h. Then, it is turned to a powder form (Karim et al., 2016). A comparison of the physical properties and the chemical composition of POCP and OPC are presented in Table 2.6. As observed, the main ingredients of POCP are SiO_2, Al_2O_3 and Fe_2O_3 of about 70.83% which meet the standard requirement to indicate pozzolanic reactivity (ASTM C 618). Kanadasan et al. (2005b) investigated the chemical composition variation of POCP from different geographical conditions and locations of Malaysia. They reported that the variation of the chemical composition in POCP is governed by the burning temperature, incineration ratio of shell and fiber and the type of soil where the tree of palm oil was grown. The variation of the pozzolanicity basis on chemical composition is presented in Table 2.7. Based on the summation of SiO_2, Fe_2O_3 and Al_2O_3 present in POCP, most of the POCP which were collected from different states in Malaysia have pozzolanic reactivity except for the state of Sabah and Sarawak. Despite the large difference among the samples from each state, generally, POC contains 60 to 75% of silica (SiO_2). Moreover, it can be seen that the specific surface area of POCP and OPC are 418 and 339 m^2/kg, respectively. POCP has sufficient specific surface area to give pozzolanic activity (Karim et al., 2016). Despite replacing cement with 50% of POC powder, almost 70% of the strength can be achieved compared to conventional mortar (Kanadasan and Razak 2015b). According to Karim et al. (2016), the particle size distribution curves of POCP and OPC are comparable and most of the particles sizes are less than 100 µm as shown in Figure 2.18. Moreover, around 50% POCP particles are smaller than 40 µm. Generally, POCP can be assumed to have similar fineness with cement (Kanadasan and Abdul Razak, 2015b). The micrograph of POCP was also investigated by Karim et al. (2016), they reported that based on the morphological analysis, POCP contains micro-pores which vary in shape and size. POCP can be categorized as generally angular and irregular as shown in Figure 2.19. POCP morphology at 100 µm magnification is presented in Figure 2.20. Irregularities can be seen clearly as some of them are flaky while some are with sharp edges. The existence of smaller voids or perforated voids can be clearly seen. EDX plotted on the POC powder specimen also confirmed the XRF results on the major SiO_2 content. This result is parallel with the findings from the XRF chemical analysis. It is also evident that POCP is generally irregular in shape whereby some flat surface layers can be also seen.

Table 2.6: Chemical composition of the POCP (Karim et al., 2016)

Chemical composition (%)	OPC	POCP
SiO_2	22.14	60.29
Al_2O_3	3.84	5.83
Fe_2O_3	2.98	4.71
SiO_2+Al_2O_3+Fe_2O_3	28.96	70.83
CaO	65.21	3.27
MgO	1.54	3.76
SO_3	3.22	0.11
K_2O	0.012	7.79
P_2O_5	0.012	3.1
TiO_2	0.002	0.13
Specific Surface area (m^2/kg)	339	418

Table 2.7: Pozzolanicity assessment on the Malaysian POCP basis of chemical composition (Karim et al., 2016)

Name of State	SiO_2 (%)	FeO_3 (%)	Al_2O_3 (%)	SiO_2 + Fe_2O_3 + Al_2O_3 (%)
Kedah	65.1	6.34	3.28	74.68
Kelantan	73.31	6.13	6	85.44
Terengganu	72.64	3.89	5.18	81.71
Penang	69.91	5.15	4.15	79.21
Perak	74.29	2.09	3.11	79.49
Pahang	60.79	15.64	7.27	83.7
Negeri Sembilan	65.64	14.41	7.56	87.4
Selangor	64.84	4.19	3.42	72.45
Melaka	57.41	10.11	4.95	72.47
Johor	69.05	3.71	4.73	77.49
Sabah	62.05	2.2	1.42	65.67
Sarawak	62.52	1.1	0.82	64.44

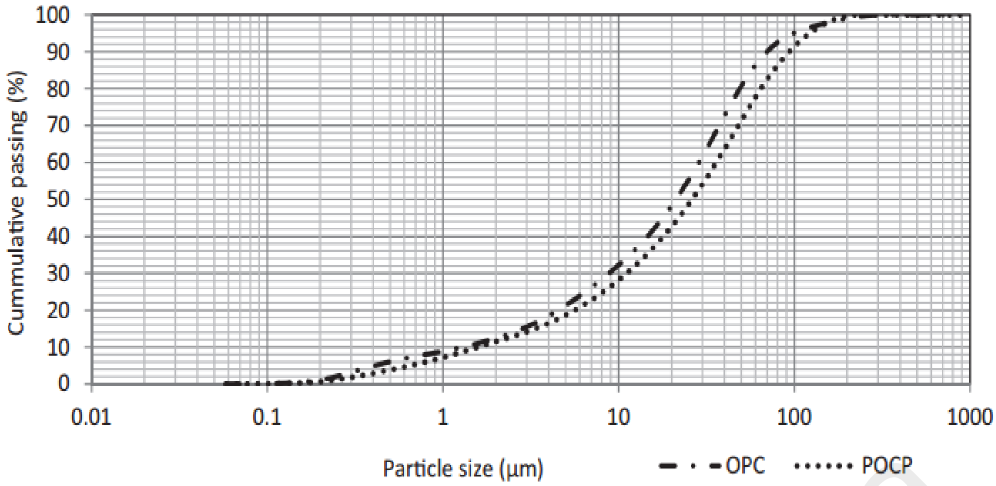


Figure 2.18: Particle size distribution of POCP and OPC (Karim et al., 2016)

Figure 2.19: Micrograph of POCP (Karim et al., 2016)

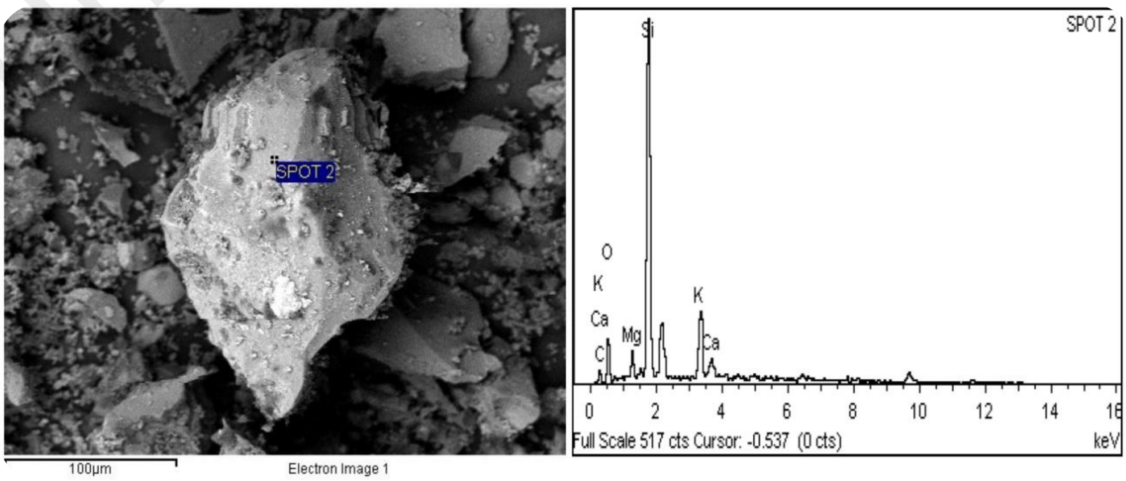


Figure 2.20: POCP particle of irregular shapes and structures with EDX results (Kanadasan and Abdul Razak, 2015b)

2.9 Summary

From the comprehensive literature analysis, a high quantities of palm oil clinker are generated in Malaysian palm oil mills as a waste with insignificant return; hence, this industrial waste can be converted into potential construction materials. It is obvious that very few research works have emphasized on the use of POC in concrete (Bashar et al., 2013; Kanadasan et al., 2014a; Roslli et al., 2002). The engineering properties and durability performance of POC concrete was not entirely investigated until today. Due to the physical properties and the high porosity of POC, the utilization of POC aggregate resulted in poor engineering properties of concrete, and no research work has been carried out to enhance the performance of POC concrete. A comprehensive research is necessary to fill the existing knowledge gaps. Taking all of these into account, this study was designed to address the sustainable exploitation of POC by ensuring the proper utilization with a suitable mix design.

CHAPTER 3: MATERIALS AND EXPERIMENTAL PROGRAM

3.1 Introduction

The chapter discusses different tests for constituent material and engineering properties used in this study. The experimental program involves a total of 32 concrete mixtures including different replacement levels of POC with natural aggregates i.e. fine and coarse. The experimental work was done in the laboratory of the Civil Engineering Department at University of Malaya. The materials, mix designs, and all tests are discussed in this chapter.

3.2 Material Characterization

3.2.1 Cement

Ordinary Portland cement (OPC) equivalent to ASTM Type-I was used during this work as the main binding material. Locally produced OPC was supplied from *TYL Cement Sdn Bhd* in bags weighting approximately 50kg. To guarantee the performance of its chemical reaction for the whole series of test conducted, the OPC used had to be of the same batch. It was well kept in airtight containers to keep it protected from moisture. The chemical composition and physical properties of the cement utilized in this work are given in Table 3.1.

3.2.2 Silica Fume (SF)

Condensed silica fume (SF) with a specific gravity of 2.2 was used as partial replacement for Portland cement by weight for the production of high strength concrete. SF grade 920-U was supplied by *Elkem* Materials, Singapore. The chemical composition of SF used in this study is presented in Table 3.1. SF was used to obtain high strength concrete and reduce the permeability of concrete thereby, inhibiting the ingress of moisture or chloride, protecting from corrosion, abrasion and chemical attack. The recommended dosage of 5-15% addition by weight of cement. However, this can be varied based on the application and the desired concrete properties. The chemical composition as given in Table 3.1 shows the SiO_2 content of 94.6%, which surpasses the minimum ASTM requirement of 85%.

Table 3.1: Chemical composition and physical properties of POCP and OPC

Chemical composition			
Oxides	OPC	POCP	SF
CaO	64	6.37	0.01
SiO_2	20.29	59.9	94.6
SO_3	2.61	0.39	0.01
Fe_2O_3	2.94	6.93	0.11
Al_2O_3	5.37	3.89	0.14
MgO	3.13	3.3	0.01
P_2O_5	0.07	3.47	0.22
K_2O	0.17	15.1	0.62
TiO_2	0.12	0.29	0.01
Mn_2O_3	0.12	-	-
Na_2O	0.24	-	0.01
Others	0.94	0.36	
Loss on ignition	1.4	1.89	-
Physical properties			
Specific Gravity (SG)	3.15	2.59	2.2

Figure 3.1: Cementitious and powder materials

3.2.3 Palm Oil Clinker Powder (POCP)

POCP was produced by grinding the POC into fine powder form (Figure 3.1) using a Los Angeles (LA) abrasion machine. The particle size distribution curves of the POCP and cement are shown in Figure 3.2. Generally, POCP can be assumed to have similar fineness with cement (Kanadasan and Abdul Razak, 2015b). The chemical properties of the POCP used in this work is presented in Table 3.1. As observed, the silica (SiO_2) content of the POCP is on the higher side. The POCP was incorporated to the mixture as a filler material to the pores due to the porosity of POC for mixtures where coarse aggregate was substituted with POC at different replacement levels.

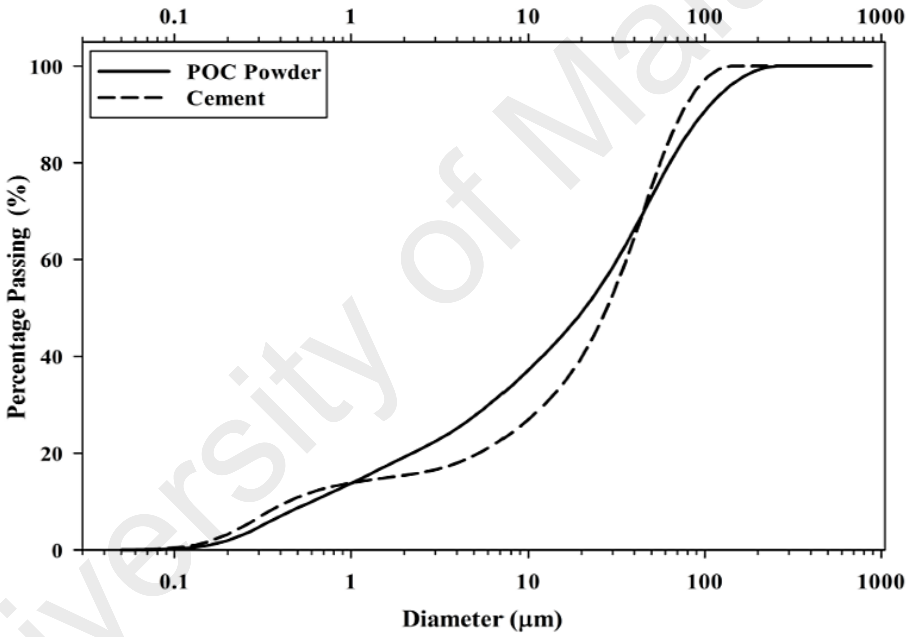


Figure 3.2: Particle size analysis for POC powder and cement

3.2.4 Coarse Aggregates

3.2.4.1 Granite Coarse

Currently, the coarse aggregates commonly used by the local concrete industries are crushed granite and gravel. In this study, crushed granite was used as a natural coarse aggregate. It was acquired directly from local quarry in *Kajang*, operated by *Kajang Rock Sdn. Bhd* (Figure 3.3). For the purpose of the experimental work, coarse aggregate was sieved to a required sizes prior usage. Aggregate with a nominal size of 14 mm was used in the production of NC, while coarse aggregate with nominal size of 10 mm was used in HSC production.

Figure 3.3: Crushed granite from local quarry

3.2.4.2 POC Coarse

The POC used in this work was collected from the solid waste of local palm oil mill as shown in Figure 3.4. It was collected in the form of large chunks (Figure 3.5). It was then crushed by using a Jew crusher machine and sieved into required sizes namely 14 to 4.75mm and 10 to 4.75mm. POC with a nominal size of 14 mm was used to replace conventional coarse aggregate in the production of NC. While POC with a nominal size of 10 mm was used to replace the conventional coarse aggregate in HSC production. Figure 3.6 shows the fine and coarse POC integrated in this work. The required tests were conducted for all types of aggregates used in this study.

Figure 3.4: Solid waste of palm oil mill

Figure 3.5: Raw POC collected from palm oil mill

Figure 3.6: Palm oil clinker (POC)

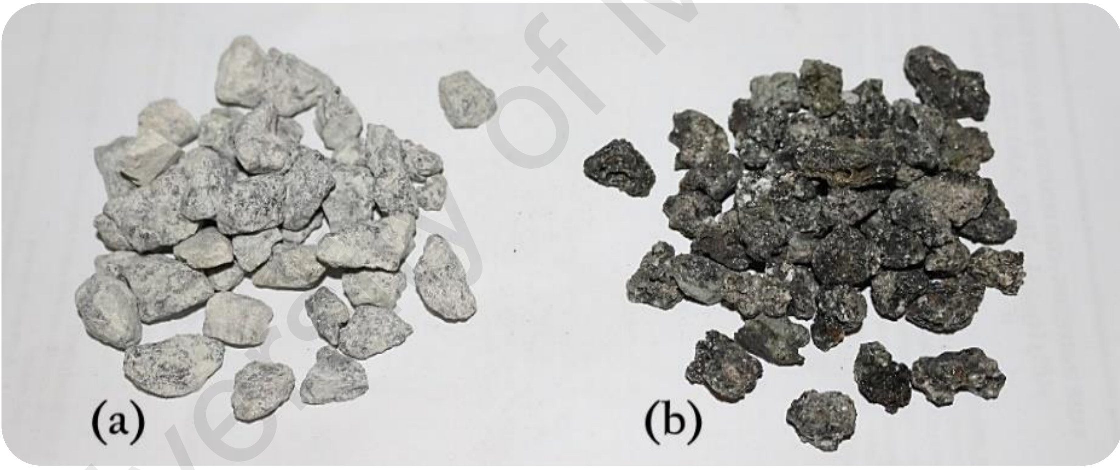


Figure 3.7: Coarse aggregate: (a) Granite; (b) POC

3.2.5 Fine Aggregates

3.2.5.1 River Sand

Fine aggregate is an important component of concrete, which is often collected from the river sand in developing countries like Malaysia. Local river sand was used as a natural fine aggregate to produce normal concrete. The river sand used in this study has fineness modulus of 2.73, specific gravity of 2.62 and maximum particle size of 4.75 mm.

3.2.5.2 Silica Sand

Silica sand with fineness modulus of 2.61, specific gravity of 2.69 and maximum particle size of 4.75 mm was used in the production of HSC. The silica sand was supplied from *L&T Mineral Sdn. Bhd.* in 50kg bags. The sand consists of four different sizes of (8-16 mesh; 2.38-1.19 mm), (16-30 mesh; 1.19-0.59mm), (30-50 mesh; 0.59-0.29mm) and (50-100 mesh; 0.29-0.15mm), the sand was combined in the ratio of 2.5:3.5:2:2, respectively to obtain a fine aggregate in compliance with the medium grading according to BS 882: 1992. The different sizes of the silica sand used in this study are shown in Figure 3.5. Specially graded sands and silica fume were employed to reduce the pore size and enhance the particle packing density to obtain a high strength concrete.

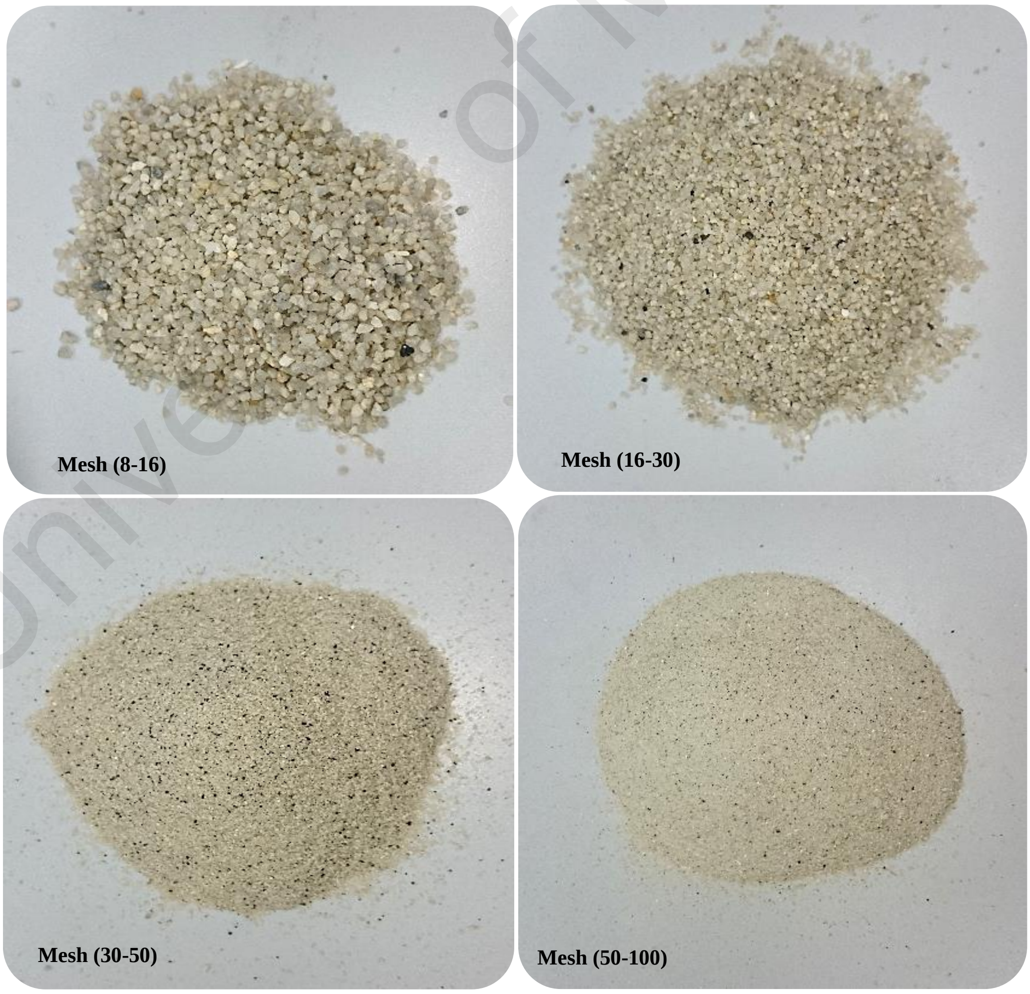


Figure 3.8: Silica sand

3.2.5.3 POC Fine

POC fine aggregate is a by-product during the production of POC coarse sieving from crushing of large chunk as shown in Figure 3.6. It was observed that after crushing the clinker, much of the crushed aggregate are fine particles. Due to the availability of this waste as fine in high volume, POC was used as partial and full replacement of natural sand to produce normal and HSC. POC fine used in this study has a fineness modulus of 2.62, specific gravity of 2.15 and maximum particle size of 4.75 mm.

3.2.6 Testing of Aggregate

Various tests were done to determine the properties of all aggregates used in this study. The type of tests and the code of practice used in testing the aggregates are summarized in Table 3.2.

Table 3.2: Testing of Aggregates

Test	Code
Sieve analysis	BS 812: Part 103, BS 882: Part 2
Bulk density	BS 812: Part 2
Specific gravity & water absorption	BS 812: Part 107
Moisture content	BS 812: Part 109
Aggregate crushing value (ACV)	BS 812- Part 110

3.2.6.1 Sieve analysis

The sieve analysis of the aggregate was performed according to BS 812: Part 103 (1992) for coarse aggregate, and BS 882: Part 2 (1992) was used to obtain the grading zone, fineness modulus and particle size distribution of the fine aggregate.

3.2.6.2 Water Absorption and Specific Gravity

Specific gravity is the ratio of the mass of a unit volume of a material to the mass of the same volume of water at stated temperature according to BS 812: Part 107. Water absorption is determined by the increase in the aggregate weight due to the ingress of water into the pores of the material excluding water adhered to the outer surface of the particles, which is expressed as a percentage of the dry weight. To determine the water absorption capacity and specific gravity of coarse aggregate, a sample of the aggregate is immersed in water for around 24 hours to appropriately fill the pores. Subsequently, the sample is moved out, surface dried and weighted. The sample is then immersed in water and weighed. Lastly, the sample is dried in oven at a temperature of 105±5°C and weighed. From the obtained weights and formulas provided by the BS 812: Part 107, the water adsorption capacity and specific gravity of coarse aggregate are calculated as follow:

$$\text{Bulk Specific Gravity (SSD)} = \frac{\text{A}}{[A-(B-C)]} \tag{3.1}$$

$$\text{Water Absorption (\%)} = \frac{(\text{A}-\text{D})}{D} \tag{3.2}$$

Where,

A = weight of SSD test sample in air (g)

B = apparent weight of basket and SSD sample in water (g)

C = apparent weight of empty basket in water (g)

D = weight of oven-dried test sample in air (g)

3.2.6.3 Moisture content

Moisture content test was performed to determine the moisture content of coarse and fine aggregates. 500g of fine and coarse aggregate are placed on the tray separately and weighted to accuracy of 0.1g. Then the sample is dried in oven at a temperature of 105±5°C for 24 hours. Subsequently, the sample is moved out and weighted to determine the dry weigh. Then the Moisture content is calculated as follow:

$$\text{Moisture content (\%)} = \frac{\text{Initial weight} - \text{Dry weight}}{\text{Dry weight}} \times 100 \tag{3.3}$$

3.2.6.4 Aggregate Crushing Value (ACV)

The aggregate crushing value gives a relative measure of the resistance of an aggregate to crushing under a gradually applied compressive load. Crushing value is a measure of the aggregate strength. The aggregate should therefore have minimum crushing value. Low crushing value generally indicates the high capability of the aggregate to sustain load, which indirectly provides good strength achievement in the concrete. The test was conducted according to BS 812-110 for all coarse aggregates used in this study including POC and granite. The test sample is dried by heating at a temperature of 105 ± 5 °C for a period of not more than 4 hours, then cool to room temperature and the mass of material comprising the test specimens before testing is recorded. The sample is then placed in a steel cylinder open-ended, of nominal 150 mm internal diameter in three equal depth of layers. Each layer being subjected to 25 strokes from the tamping rod, dropping from a height of 50 mm above the surface of the aggregate to distribute the layer evenly over the surface. The top surface is leveled carefully, and the load is then applied at a uniform rate so that the required force of 400 KN is reached in 10 min ± 30 sec. Then load is released, and the weight of the aggregate is recorded as (M_1) to the nearest gram. The whole of the test sample is sieved on 2.36 mm. The mass of the fraction passing and retained in the sieve is weighted and recorded as M_2 and M_3, respectively. If the total mass of the two individual fractions (M_2 + M_3) differs from the initial mass (M1) by more than 10 g, the result is rejected, and further sample is tested. ACV expressed as a percentage of the mass of fines formed to the total mass of the test sample from the following equation:

$$\text{Aggregate crushing value } (ACV) = \frac{\mathrm{M}_2}{\mathrm{M}_1} \times 100 \qquad (3.4)$$

Where, M_1= the mass of the test specimens (g)

M_2 = the mass of the material passing the 2.36 mm test sieve (g)

3.2.7 Superplasticizers

To enhance the concrete workability, two types of superplasticizer were used in this study:

SP1: Sika ViscoCrete-2199 is a high range water-reducing admixture used as a superplasticizer in the production of NC. Its chemical base consists of a modified polycarboxylate. According to BS 5075, this admixture is free of chloride and is suitable for all types of Portland cement including Sulphate Resistant Cement (SRC).

SP2: Sika Viscocrete-2044 is a third-generation superplasticizer, was used in HSC production, with specific gravity of 1.06 (at 20° C). This type of superplasticizer is suitable for the production of concrete mixes with very high-water reduction.

3.3 Experimental Program

Normal and high strength concrete with a compressive strength of 40 and 90 MPa, respectively, were the design strength for the purpose of this study. To allow independency of the mix design method, two different concrete mix design methods were employed. The normal grade concrete has a compressive strength of 40 MPa was designed by using department of environment (DOE) mix design method with a water-cement ratio of 0.53 and slump range of 100±25 mm; whereas the HSC, which has a compressive strength of 90 MPa was designed by using the Sherbrooke mix design method with water-binder ratio of 0.30. It was essential that the optimum proportions be selected based on the mix design method, taking note of the characteristics of all the materials used. The research program involved several trial mixes which were conducted prior attaining the final mix proportions for the control mix. The experimental program involves two stages of incorporation of POC to the mixtures. At first stage, crushed POC was partially and fully replaced with natural aggregates i.e. coarse and fine. The percentage of POC substitutes used are 0%, 20%, 40%, 60%, 80% and 100% of the total volume of coarse and fine aggregate, separately.

The second stage is the final mix proportions after incorporating POCP to 6 levels of POC coarse replacement. Particle-packing (PP) method was used for the mixes where the coarse aggregate was substituted with POC to measure the total voids in the mixtures. To enhance the engineering properties of POC concrete, addition of POCP was then incorporated to the mixes as a suitable filler material to the voids of POC at different substitution levels, while maintaining the other mix constituents. POCP was used as means to maximize the usage of palm oil mill waste in concrete production.

Fresh and hardness properties of the concrete mixes with and without POCP were investigated and compared with the control concrete, which was prepared using natural aggregates. The flow chart of the experimental program for incorporation of POC in the concrete is presented in Figure 3.9.

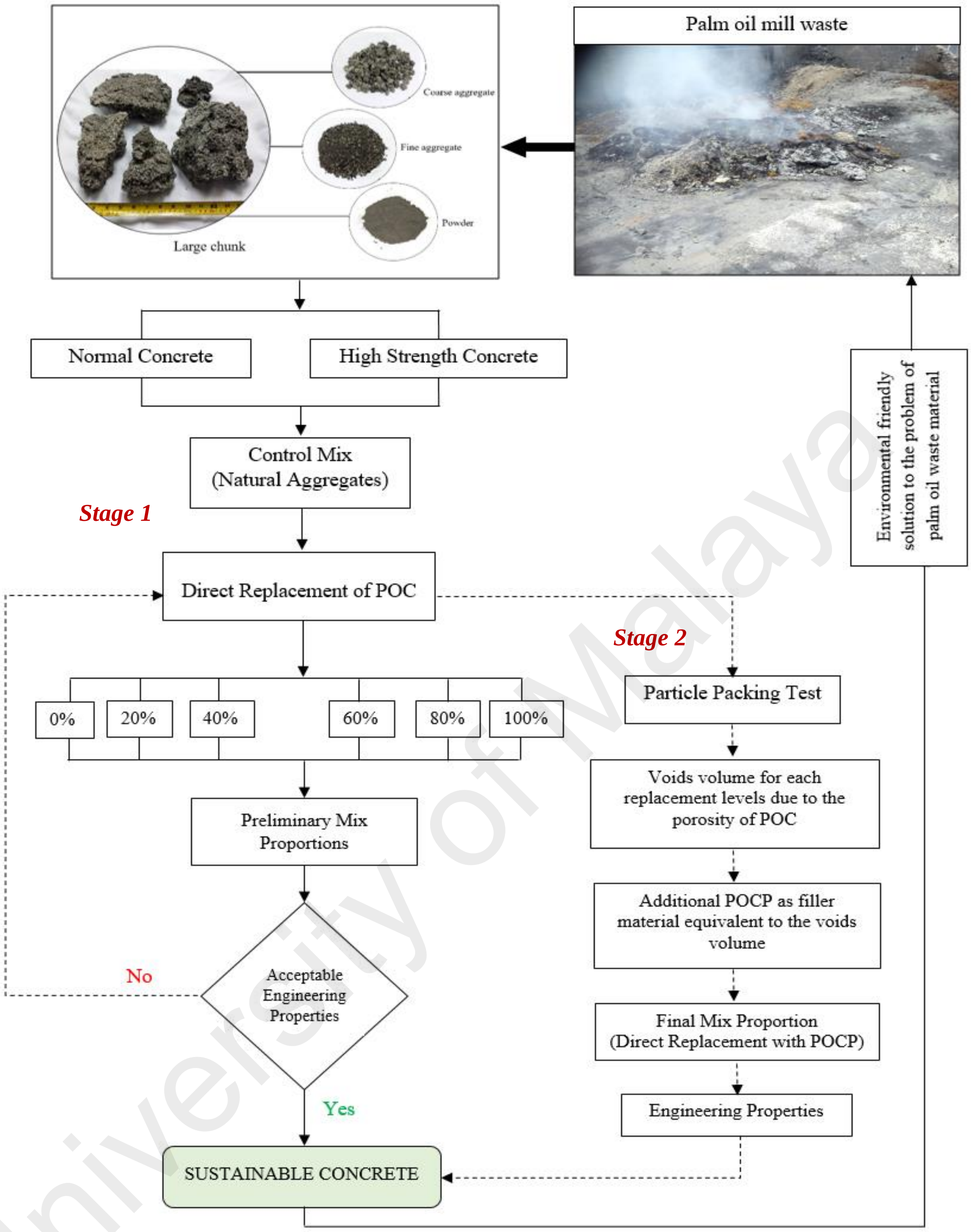


Figure 3.9: Flow chart of the experimental program

3.3.1 Normal Concrete

3.3.1.1 Mix Design Development

Mix design can be defined as the selection of concrete ingredients and their proportions. It involves the process of choosing the correct proportion of cement, aggregates i.e. coarse and fine, water, chemical and mineral admixtures to produce concrete that is economical and possesses certain properties such as strength, durability and a required consistency. DOE method was used to determine the concrete properties like workability, density, durability requirement and strength at a specific age. DOE mix design method is carried out in five stages as presented in Figure 3.10, details of the method procedure are given in appendix A. The basic mixture proportions were corrected considering the absorption and moisture content of aggregates used in the mixtures. The mix of NC was designed to achieve a compressive strength of 40 MPa at 28 days. The workability was maintained in the range of 100±25 mm slump. To make sure the concrete exhibits the targeted strength and slump, trial mixes were carried out before getting the actual mix proportion of control concrete. The details of the mix proportions of the control concrete and the mixes of the two stages of incorporating POC as aggregates are given in the following sub-sections:

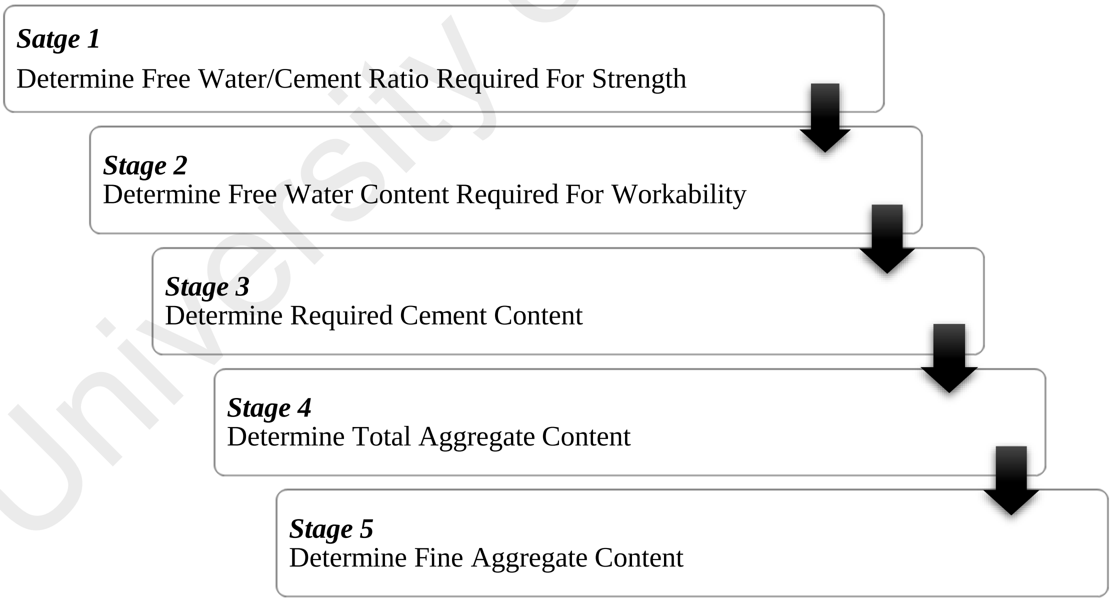


Figure 3.10: General procedure of DOE mix design

3.3.1.2 Direct Replacement

Four types of aggregate were used in this part of study including; river sand as natural fine aggregate, crushed granite rocks used as natural coarse aggregate, POC, which obtained from a local palm oil mill, was crushed to be used as a replacement of the natural coarse and fine aggregates. All coarse aggregates used had a maximum size of 14mm whereas the fraction with size less than 4.75 mm were used as fine aggregate. POC replacement was carried out for both coarse and fine aggregate, separately. The amount of POC substitutes used are 0%, 20%, 40%, 60%, 80% and 100% of the total volume of the aggregates. All the mixes had a constant water to cement ratio and cement content of 0.53 and 420 kg/m^3, respectively to observe the effect of POC replacement on fresh and hardened properties of the concretes. Details of the constituent materials proportion of all concrete mixes are presented in Table 3.3. The control mix (M0) was prepared by using natural aggregates. Series POC and POCF represent the various percentages of coarse and fine aggregate substitution with POC, respectively.

Table 3.3: Mixture proportions of the direct replacement for normal concrete

Replacement level	ID	w/c Ratio	Mix proportion (*Kg/m^3*)				
			Cement	Fine Aggregate		Coarse Aggregate	
				River Sand	POC	Granite	POC
Control Mix	**M0**	0.53	420	760	-	1007	-
Coarse Aggregate Replacement (Series POC)							
20%	**POC20**	0.53	420	760	-	806	131
40%	**POC40**	0.53	420	760	-	604	263
60%	**POC60**	0.53	420	760	-	402	394
80%	**POC80**	0.53	420	760	-	201	526
100%	**POC100**	0.53	420	760	-	-	657
Fine Aggregate Replacement (Series POCF)							
20%	**POCF20**	0.53	420	608	123	1007	-
40%	**POCF40**	0.53	420	456	246	1007	-
60%	**POCF60**	0.53	420	304	369	1007	-
80%	**POCF80**	0.53	420	152	492	1007	-
100%	**POCF100**	0.53	420	-	614	1007	-

3.3.1.3 Direct Replacement with POCP

There are not many guidelines available in literature on how to choose the quantity of powder or paste required to improve such concrete. Therefore, Particle-packing method was suggested to be used for each substitution levels of POC coarse to determine the volume of voids due to the porosity of POC. PP method gives an insight on the interaction between POC and natural aggregates. To enhance the PP density of concrete, small particles should be selected to fill up the pores between the large particles (Mangulkar and Jamkar, 2013). Steps of using PP method to measure the voids of POC for all substitution levels are as follow:

Step 1: All the aggregate particles are checked to ensure they have been soaked in water for 24 hours. They are later brought into the saturated surface dry (SSD) condition to avoid any loss of fluid through absorption during the PP test.

Step 2: The combination of the aggregates i.e. POC coarse, granite coarse and river sand with proportion based on the mix designed by DOE method as tabulated in Table 3.3 is prepared on the baseplate. They are thoroughly mixed using a scoop and trowel to obtain a homogenous mix. It was later placed into the container in a loosely packed state as shown in Figure 3.11.

Step 3: A known volume of clean potable water was prepared. Subsequently, the water is poured slowly into the container which is filled with the aggregates.

Step 4: Once the water level reaches the top surface of the container, the water level is checked consecutively every 30 second for a period of 2 minutes. This is basically to enable water to fill up all the voids between the aggregates. Water is constantly added if there is a reduction in the level. The amount of water used, represents the total amount of voids present. this volume represents the paste volume that will be required to coat and lubricate the aggregate particles. It was observed that mixes incorporated less POC content have more void volume as compared to the mixes with high POC contents as shown in Figure 3.12.

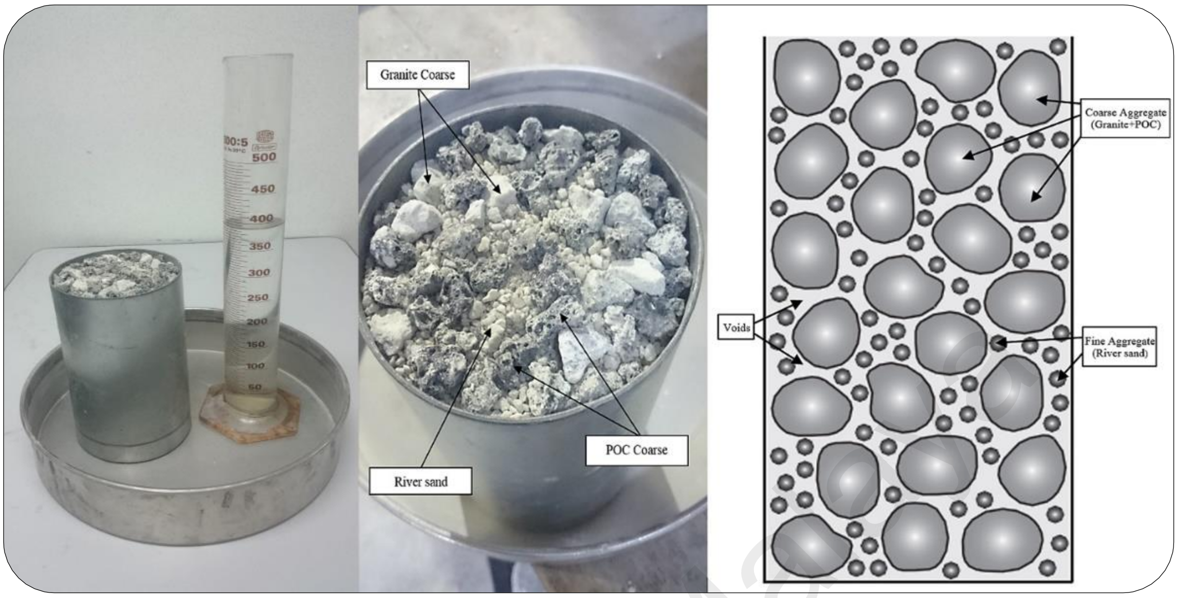
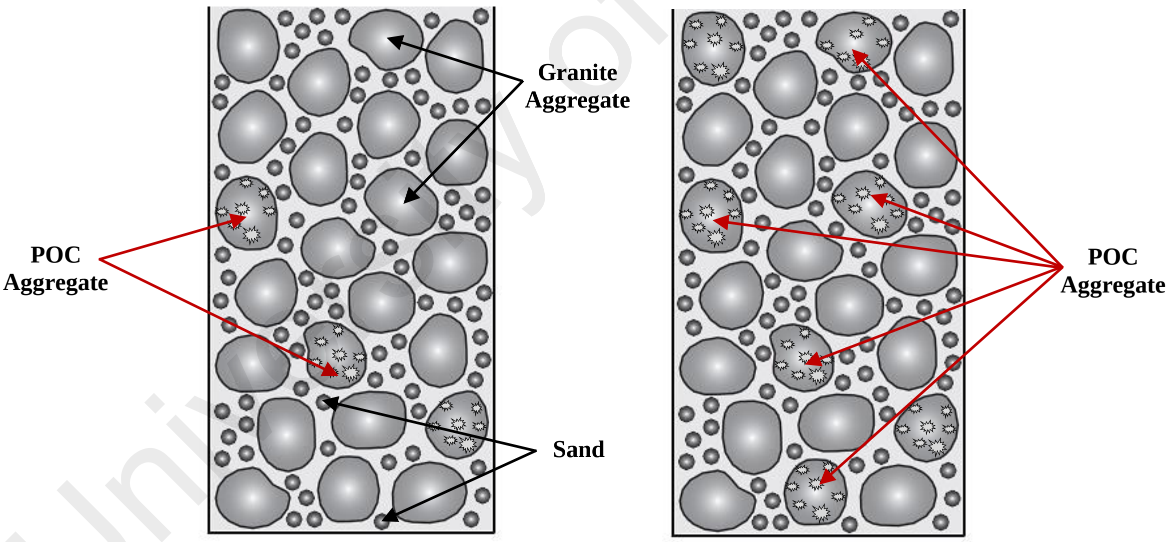


Figure 3.11: Particle packing (PP) test



(a) (b)

Figure 3.12: POC concrete mixes: (a) less POC contents; (b) more POC contents

It is important to design concrete structures and mixtures in such a way that the environmental impact is minimized. As such, palm oil clinker powder (POCP), which was produced by ball mill grinding process of POC was selected as an appropriate filler material to the voids of POC. Utilization of POCP as filler material was to enhance the fresh and hardened properties of POC concrete. Additionally, utilization of POCP is also a means of maximizing the use of palm oil mill wastes in concrete production. The general procedure of determination of the POCP required for each substitution level of POC coarse is shown in Figure 3.13 and the detailed calculations are given in appendix C.

REQUIRED POCP

↓

Particle Packing Test

↓

Void volume for each replacement level (m^3/m^3)

↓

Percentage of void volume increment for each replacement level compared to the control mix (%)

↓

Increase the control paste volume with the percentage of void increment

↓

Calculate the required volume of POCP for each replacement level

Figure 3.13: Flow chart for determine the required POCP

Based on the PP results, the final mix proportions after incorporating POCP to six levels of POC coarse replacement ranging from 0% to 100% of the total volume of coarse aggregate are presented in Table 3.4. Trial concrete mixes with different SP dosage was conducted for each replacement level to determine the optimum dosage of SP to achieve the slump in the target range. Figure 3.14 presents the total powder and superplasticizer (SP) dosage required for different substitution levels of POC to get a constant slump in the range of 100±25mm. The comparison was done to determine the effect of the POCP addition on fresh and hardened properties of POC concrete.

Table 3.4: mix proportion for the direct replacement with POCP for normal concrete

Replacement level	ID	Cement (kg/m^3)	POCP (kg/m^3)	w/p ratio	Aggregates (kg/m^3)		
					Fine	Coarse	
					River Sand	Granite	POC
Control mix	**M0**	420	0	0.53	760	1007	0
20%	**POCP20**	420	70	0.51	760	806	132
40%	**POCP40**	420	93	0.48	760	604	263
60%	**POCP60**	420	108	0.46	760	403	394
80%	**POCP80**	420	156	0.45	760	201	526
100%	**POCP100**	420	203	0.43	760	0	657

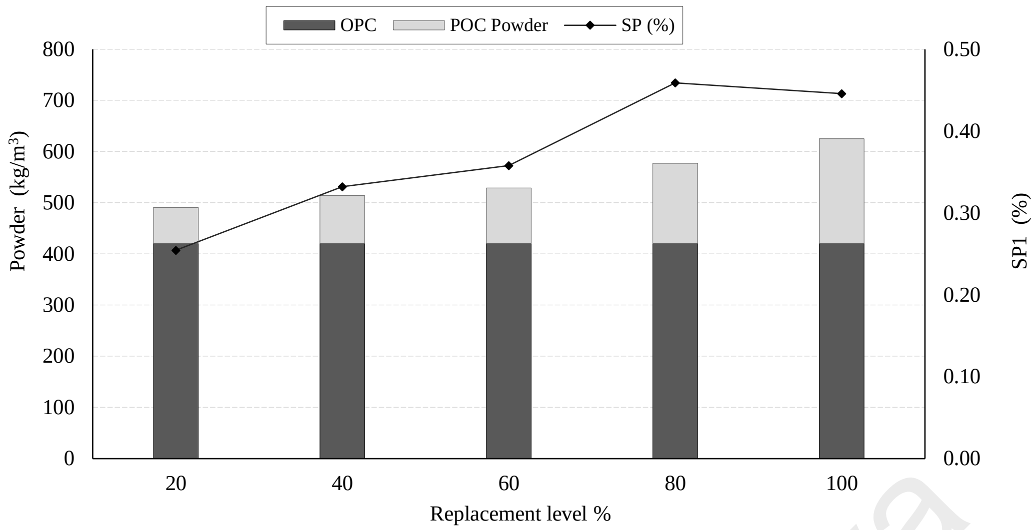


Figure 3.14: POCP and SP dosage for each replacement level of POCP mixes

3.3.2 High Strength Concrete

3.3.2.1 Sherbrook Design Mix

HSC is a type of concrete mixture that has appropriate workability, develops high strength and possesses excellent durability properties throughout its intended service life (Forster, 1994). HSC usually exhibits higher strength, denser microstructure and a much lower permeability as compared with ordinary concrete (Gesoglu et al., 2016). This is typically achieved by using mineral admixture and superplasticizer to enable the use of a very low water to cement ratio. Sobolev (2004) reported that using w/c ratio of 0.32 - 0.19 increase the compressive strength of concrete to give a super high strength concrete up to 135 MPa. Different methods of mix proportioning arise different amount of composite materials proportions even though targeting the similar strength. The incorporation of pozzolanic materials is currently a generally used technique towards attaining a high strength concrete. SF, which is a promising by-product from the production of silicon and ferrosilicon, is one of the pozzolanic materials and act as the key access to the gateway to achieve high strength concrete. Behnood and Ziari (2008) reported that concrete supplemented with SF as a partial substitution of cement exhibited an enhanced compressive strength mainly because of the improvement in the strength of cement paste matrix. It contributes both pozzolanic and filler effect to the concrete, but most dominantly in filler effect due to its excessively fine particle size. Silica fume can fill the voids between the next larger class particles cement to form a dense material. Furthermore, the addition of silica fume densifies the packing in the interfacial transition zone, such that the porosity in this region is substantially reduced (Gesoglu et al., 2016). Superplastisizer also enables the cement grains to have a more uniform packing reducing the porosity of the paste, thereby, improving the density (Gesoglu et al., 2016).

In this study, HSC was designed based on Sherbrooke mix design method (Aitcin, 1995), which was proposed by Professor Pierre-Claude Aitcin of Universite de Sherbrooke, Quebec, Canada. It calculates the mixture composition for non-air entrained high-performance concrete and follows the same approach as in ACI 211-1. The design approach combines the empirical results and mathematical calculation based on the absolute volume method, which assumes that the volume of the resultant compacted concrete is equal to the sum of absolute volumes of all the components. The general procedure of Sherbrooke is shown in Figure 3.15, and details of the Sherbrook method procedure are given in Appendix B. Trial mixes were carried out to determine the suitable water/binder ratio and cement content required to obtain the desired strength and to determine the suitable superplasticizer dosage required to achieve the targeted workability. HSC was designed to achieve a compressive strength of 90MPa at 28 days and the workability was maintained in the range of 150±25 mm slump.

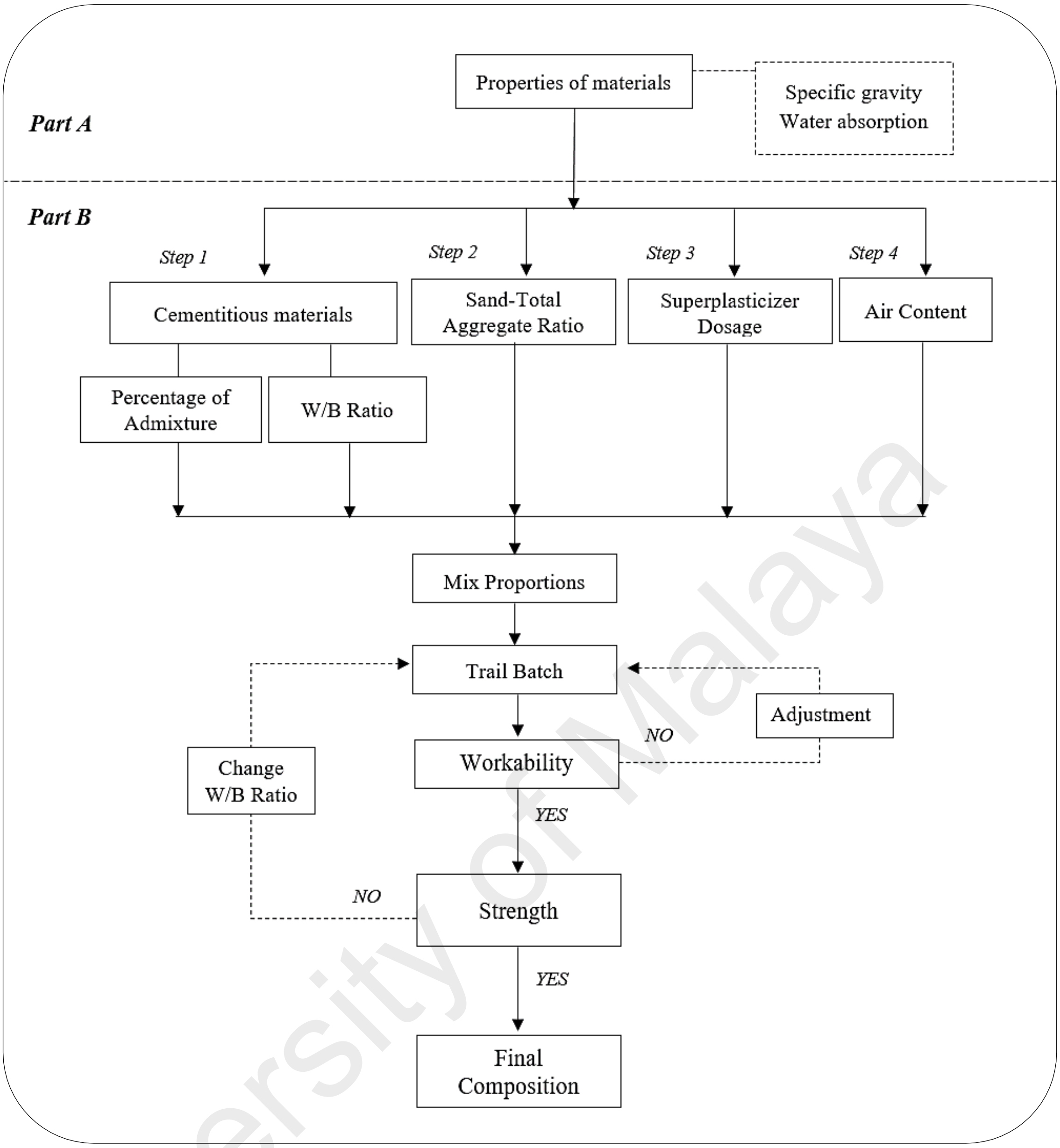


Figure 3.15: Flow chart of Sherbrook mix design method

3.3.2.2 Direct Replacement

Four types of aggregate were used in the production of HSC which include; silica sand as natural fine aggregate, crushed granite rocks used as natural coarse aggregate, POC was crushed to be used as a replacement of natural coarse and fine aggregates. POC with volume fraction passing 10 mm sieve and retained on 4.75 mm sieve was used as coarse aggregate while those with size less than 4.75 mm were used as fine aggregate. POC replacement was conducted for both fine and coarse aggregate, separately. The percentage of POC replacement used are 0%, 20%, 40%, 60%, 80% and 100% of the total volume of the aggregates. All HPOC mixes had a constant cement content and water to binder ratio of 595 kg/m3 and 0.3 respectively in order to observe the effect of POC replacement on fresh and hardened concrete properties. SF was added to all the mixes by replacing roughly 12% of cement content. Addition of micro-silica to cement pastes or concretes leads to lower workability. Such effect can result in higher water demand to maintain a constant slump. Hence, superplasticizer was added by weight of the total binder. All mix design parameters were maintained constant except for the coarse and fine aggregates constituents. The high range water-reducing Sika ViscoCrete-2044 superplasticizer of polycarboxylate base was added at constant rate of 1.5% of the binder content weight for all mixes to ensure an effective comparison. This would also allow for comparisons to be made between the HSC and NC mixes. Details of the constituent materials proportion of all HSC mixes are presented in Table 3.5. Control mix (H0) was prepared using natural aggregates. Series HPOC and HPOCF represent the different percentages of coarse and fine aggregates replacement with POC, respectively.

Table 3.5: Mixture proportions of the direct replacement for HSC

Replacement level	ID	w/b Ratio	Mix proportion (*kg/m³*)						SP2 (%)
			OPC	SF	Fine Aggregate		Coarse Aggregate		
					Silica Sand	POC	Granite	POC	
Control Mix	**H0**	0.3	520	75	715	-	1050	-	1.5
Coarse Aggregate Replacement (Series HPOC)									
20%	HPOC20	0.3	520	75	715	-	840	147	1.5
40%	HPOC40	0.3	520	75	715	-	630	295	1.5
60%	HPOC60	0.3	520	75	715	-	420	442	1.5
80%	HPOC80	0.3	520	75	715	-	210	589	1.5
100%	HPOC100	0.3	520	75	715	-	-	737	1.5
Fine Aggregate Replacement (Series HPOCF)									
20%	HPOCF20	0.3	520	75	572	114	1050	-	1.5
40%	HPOCF40	0.3	520	75	429	229	1050	-	1.5
60%	HPOCF60	0.3	520	75	286	343	1050	-	1.5
80%	HPOCF80	0.3	520	75	143	457	1050	-	1.5
100%	HPOCF100	0.3	520	75	-	571	1050	-	1.5

3.3.2.3 Direct Replacement with POCP

Particle-packing (PP) method was then conducted for all replacement levels of HPOC mixes to determine the volume of voids the POC mixtures. Steps of using PP method to measure the voids at all substitution levels are as given in section 3.3.1.3. POCP was also selected as the suitable filler material to the voids of POC. The general procedure to determine the POCP required for each substitution level of POC coarse is shown in Figure 3.13 and the detailed calculations are given in appendix C. Based on the PP results, the final mix proportions after incorporating POCP to the six replacement levels of HPOC mixes are presented in Table 3.6. Figure 3.16 shows the total powder and superplasticizer (SP2) dosage required for different substitution levels of POC coarse to attain a constant slump in the range of 150±25mm. Comparison was conducted to determine the effect of the addition of POCP on fresh and hardened properties of HPOC concretes.

Table 3.6: Mix proportion for the direct replacement with POCP for HSC

Replacement level	ID	OPC (kg/m^3)	SF (kg/m^3)	POCP (kg/m^3)	W/P Ratio	Aggregates (kg/m^3)		
						Fine	Coarse	
						Silica Sand	Granite	POC
Control mix	H0	520	75	0	0.3	715	1050	0
20%	HPOCP20	520	75	48	0.28	715	840	147
40%	HPOCP40	520	75	88	0.26	715	630	295
60%	HPOCP60	520	75	118	0.25	715	420	442
80%	HPOCP80	520	75	158	0.24	715	210	589
100%	HPOCP100	520	75	178	0.23	715	0	737

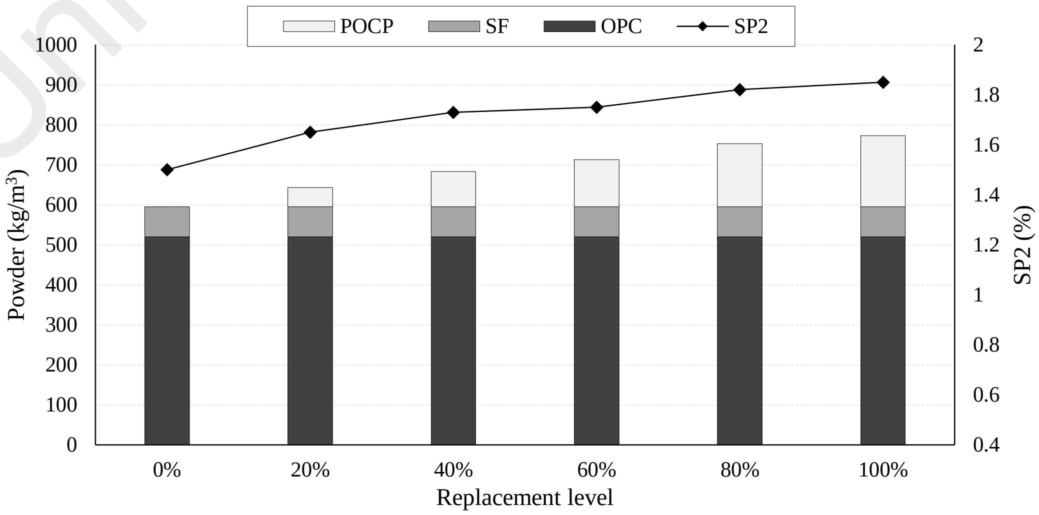


Figure 3.16: Total powder and SP dosage for each replacement level of POCP mixes

3.3.3 Mixing Procedure

3.3.3.1 Normal Concrete

I. Direct Replacement

Mixing procedure has a great effect on the workability and homogeneity and thus the strength of the mix. Before mixing started, the mixer should be kept clean, moist and free from excess water. The fine and coarse aggregates were dry mixed with cement for 3 minutes to achieve a homogenous mix, and subsequently mix with two-third of the total water for 3 min. Afterward, the remaining water was added and mixed continuously for another 5 min to complete the entire mixing process.

II. Direct Replacement with POCP

POC coarse with POCP were dry mixed for 5 minutes in order to fill up the surface voids of POC coarse. Figure 3.17 shows the coating of POCP into the pores during the mixing process. Then the remaining aggregates i.e. granite and sand with cement were added and allowed to dry mix for additional 3 minutes to properly coat the materials. After that, two-third of the mixing water was added and allowed to mix for 3 minutes. The remaining water and SP were gradually added to the mixture. The concrete mix was subjected to additional mixing for about 5 minutes to ensure a homogenous mix was obtained.

Figure 3.17: POC particle: (**a**) pre-coating; (**b**) after coating.

3.3.3.2 High Strength Concrete

I. Direct Replacement

The ingredients of the concrete mix of aggregates i.e. granite, POC and silica sand were placed into the laboratory concrete mixer and dry mixed for 3 minutes. Then the cement and SF were added and while dry mixing continued for another 3 minutes to ensure a homogeneous mix is obtained. The next step was addition of 75% of the total amount of water and allowed to mix for 3 minutes. The last stage is a gradual addition of the remaining of water along with the superplasticizer and mixed continuously for another 5 minutes to complete the entire mixing process.

II. Direct Replacement with POCP

The POC coarse aggregate was dry mixed for 5 minutes with POCP to fill up the voids of the POC coarse. Then the remaining aggregates i.e. silica sand and granite were added and allowed to dry mix for additional 3 minutes. Cement and silica fume were added and dry mix continued for another 3 minutes for proper coating of the materials. After that two-third of the mixing water was added and allowed to mix for 3 minutes. The remaining water and SP were gradually added to the mixture. The concrete mix was subjected to additional mixing for about 5 min to ensure a homogenous mix was obtained.

3.3.4 Preparation of Concrete Specimens

After the entire mixing process, the fresh property was determined by measuring the workability and fresh density. The quantity of concrete was always prepared 20% in excess of the required amount. The fresh concrete was cast in steel moulds as shown in Figure 3.18. Prior casting, the surface of the moulds were cleaned and the interior faces of the moulds were applied with a thin layer of oil to facilitate the de-moulding process. Fresh concrete was casted in three layers; each layer was compacted using a vibration tables. After the final layer are compacted, the top was leveled to provide a smooth and flat surface and then covered with gunnysacks to prevent moisture loss and to minimize plastic shrinkage. The specimens were de-moulded after 24 hours as shown in Figure 3.19 and then subjected to full water curing tank until the date of hardened concrete test. Details of the types of hardened tests and the moulds sizes used in this study are presented in Table 3.7. The direct replacement mixes were testes in different ages up to 28 days. While, the mixes with additional POCP were tested up to 180 days.

Table 3.7: Details of the specimens for hardened tests

Hardened Tests	Age	Number	Mould	Total
Compressive strength & UPV	3 days	3	Cube (100mm)	33
	7 days	3		
	14 days	3		
	28 days	3		
	56 days	3		
	90 days	3		
	180 days	3		
Water absorption	7 days	3		
	28 days	3		
	90 days	3		
	180 days	3		
Flexural Test	28 days	3	Prism (100 x 100 x 500) mm	9
	56 days	3		
	90 days	3		
Shrinkage	7 days onward	3	prism (100 x 100 x 300) mm	3
Splitting tensile	7 days	3	Cylinder (100 dia. x 200 length) mm	18
	28 days	3		
	56 days	3		
	90 days	3		
RCPT	28 days	2		
	90 days	2		
	180 days	2		
Modulus of Elasticity	28 days	2	Cylinder (150 dia. x 300 length) mm	6
	90 days	2		
	180 days	2		

Figure 3.18: The moulds and vibration table used for concrete casting

Figure 3.19: De-molded concrete specimens

3.3.5 Fresh Concrete Tests

The determination of the properties of the fresh concrete is to investigate the effect of POC aggregates incorporation and POCP as filler material on the uniformity and workability characterization of concrete as well as the fresh density.

3.3.5.1 Slump

The slump test was performed to measure the consistency of the concrete and is considered as the standard test for concrete workability. The principle of slump test is based on measurement of flow property of concrete under self-weight after the standard compaction according to BS 1881: Part 102. It is not only appropriate for medium and high workability concrete, but also sensitive to small changes in water content. Furthermore, it is very simple and appropriate for site use. The apparatus used is a cone with bottom diameter of 200 mm and a height of 300 mm together with 600 mm long tamping rod. Before starting the test, it is important to ensure that the internal surface of the cone is clean. The cone is placed on a smooth, horizontal, rigid and non-absorbent surface that is free from shock and vibration. Firstly, the cone is filled with concrete in three equal layers and each layer is compacted with 25 strokes of tamping rod. Then the cone is gently raised, and the concrete released to slump under its own weight. The slump is measured by using the upturn cone and slump rod as a guide. Koehler and Fowler (2003) proposed various description of workability for fresh concrete based on different magnitude. The approximate slump magnitude for different workability is given in Table 3.8.

Table 3.8: The degree of workability (Koehler et al., 2003)

Degree of workability	Slump (mm)
No Slump	0
Very low	0-25
Low	25-50
Medium	50-100
High	100-180
Very high	180 to collapse

3.3.5.2 Fresh Density

The density of fresh concrete was measured in accordance to BS1881: Part 107 . It can be obtained by weighing the compacted fresh concrete in a container of known volume and mass. The top of container is cleaned of any excess concrete. The density of fresh concrete is determined by using the following equation:

$$\rho = \frac{\mathrm{M}}{\mathrm{V}} \qquad (3.6)$$

Where, ρ = density of fresh concrete (kg/m^3)

M = mass (kg)

V = container volume (m^3)

3.3.6 Hardened Concrete Tests

All the tests performed on the hardened concrete were used to evaluate the mechanical properties and durability of the concrete, which include compressive strength, static modulus of elasticity, splitting tensile strength, flexural strength, ultrasonic pulse velocity, water absorption capacity, drying shrinkage and chloride penetrability resistance.

3.3.6.1 Hardened Density

The test was carried out according to BS EN 12390-7. At 28 days, Cubes of 100 mm^3 were measured for its mass and dimension. The dimensions of the specimens were measured to calculate its volume. The density was calculated using Equation 3.7 and the average value of three specimens is reported as the hardened density of concrete.

$$\rho = \frac{\mathrm{M}}{\mathrm{V}} \qquad (3.7)$$

Where, ρ = hardened density of concrete (kg/m^3)

M = mass (kg)

V = specimen volume (m^3)

3.3.6.2 Compressive Strength

The compressive strength test was performed based on BS EN 12390-3 (2009). Cube of 100mm were tested using compression machine manufactured by Engineering *Laboratory Equipment* (ELE) with maximum capacity of 3000kN. The specimen is placed with the flat smooth surface in contact with the platens of the testing machine as presented in Figure 3.20. The average value of three specimens is reported as the compressive strength except at the age of 28 days that an average of 6 specimens was reported for hardened concrete test to calculate the coefficient of variation of the direct mixes. The compressive strength is determined by dividing the maximum applied load at failure by surface area of the specimen as shown in the following equation:

$$f_c = \frac{F}{A_c} \qquad (3.7)$$

Where, f_c = Compressive strength (MPa)

F = Maximum load at failure (N)

A_c = cross-sectional area of the specimen (mm^2)

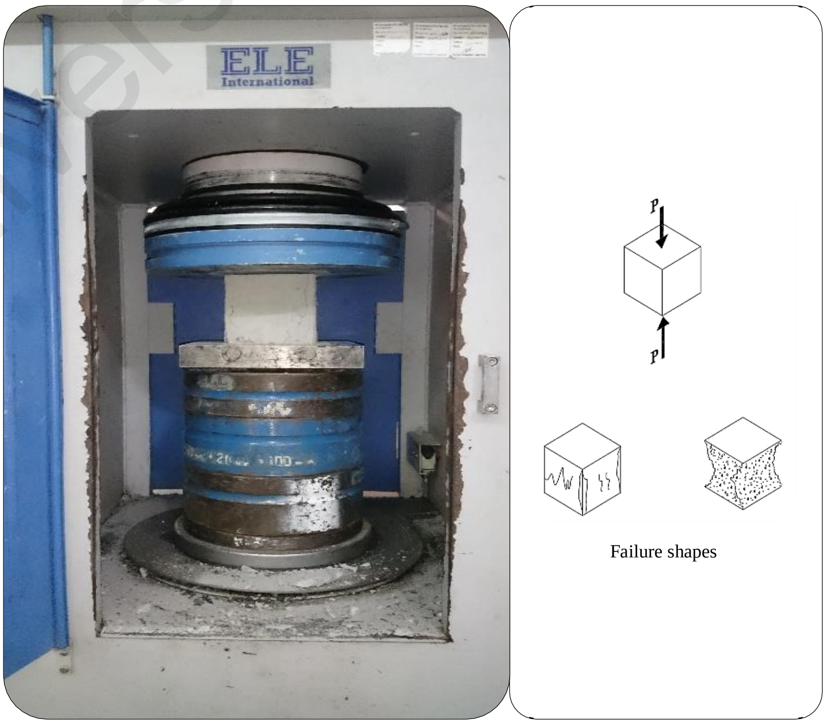


Figure 3.20: Compressive strength test

3.3.6.3 Splitting Tensile Strength

The splitting tensile strength test was carried out in accordance to BS EN 12390-6 (2009) on a cylinder of (100mm dia.× 200mm length) at the age of 7, 28, 56 and 90 days. The specimen is positioned on the centering jig with packing strips placed along the top and bottom as shown in Figure 3.21. Hardboard packing strips made of plywood were used to prevent local failure. The load is applied continuously at the rate of 0.785 KN/sec until failure occurs. Then the maximum load at the point of failure is noted and the splitting tensile strength is determined by using the following equation:

$$f_{st} = \frac{2P}{\pi \, ld} \tag{3.8}$$

Where, f_{st} = Splitting tensile (MPa)

P = maximum failure load (KN)

l = specimen length (mm)

d = diameter of cylindrical (mm)

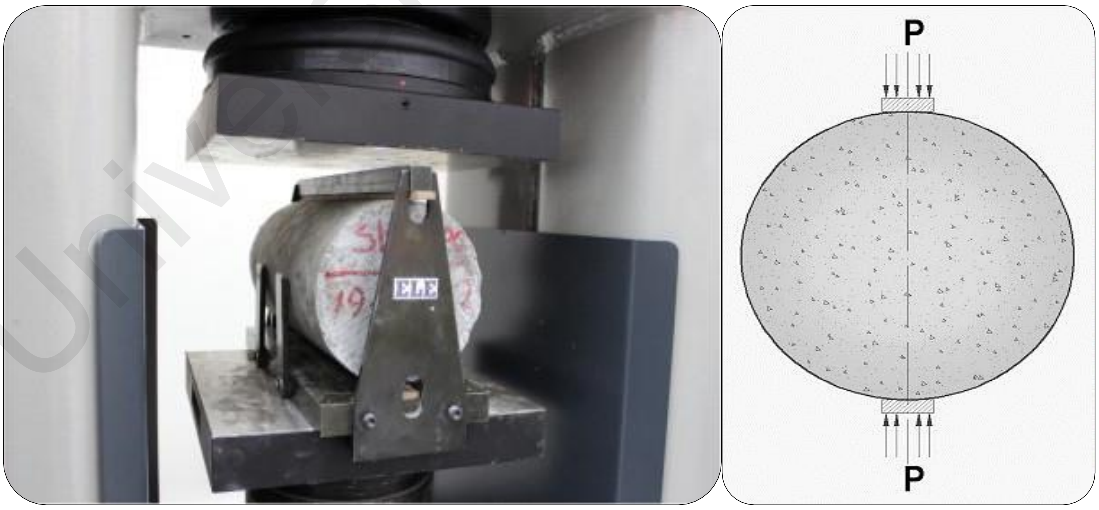


Figure 3.21: Splitting tensile test

3.3.6.4 Flexural Strength

The Flexural strength test was performed out in according to BS EN 12390-5 (2009). A concrete beam of $(100\text{mm} \times 100\text{mm} \times 500\text{mm})$ is subjected to flexure using symmetrical two-point loading with pace of 0.067 KN/sec using an ELE machine of 3000KN capacity as shown in Figure 3.22. The load is applied continuously at the mentioned rate until failure occurred and the pick load at the failure is recorded. The flexural strength, also known as the modulus of rupture is calculated by the following equation:

$$f_r = \frac{PL}{bd^2} \tag{3.9}$$

Where, f_r = Flexural strength (MPa)

P = maximum failure load (KN)

L = span length (mm)

b = width of the beam (mm)

d = depth of the beam (mm)

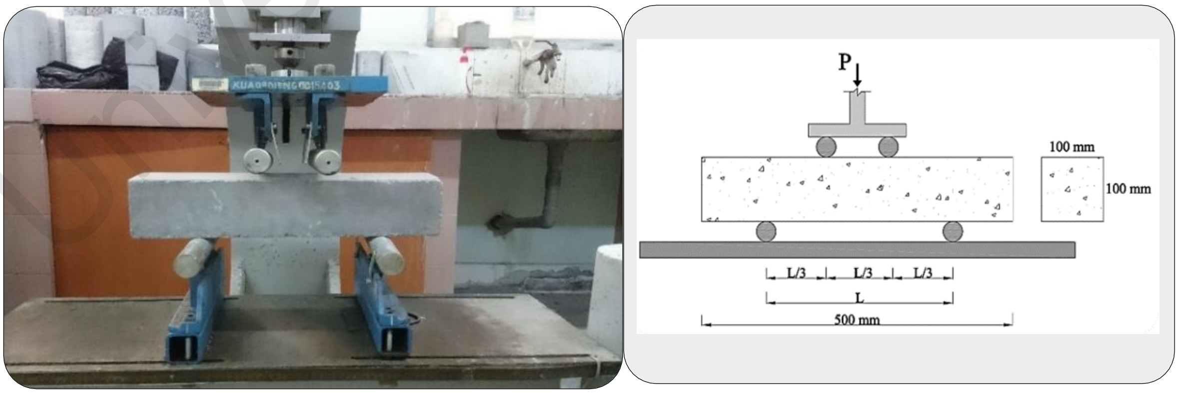


Figure 3.22: Flexural strength test

3.3.6.5 Ultrasonic Pulse Velocity (UPV)

Non-destructive test (NDT) is an experimental method used in science and industry to determine the properties of material without causing any damage. UPV is a non-destructive test that allows engineers to perform continuous concrete evaluation during the service life of concrete structure. The obtained results from UPV test can be used for diagnosis, prognosis and quality control. The quality of the building materials is related to its rigidity. UPV test can be used to measure the quality of concrete structure, estimate the mechanical properties, the compressive strength and modulus of elasticity. Therefore, there is a continuous interest in the development of useful correlation between the UPV values and compressive strength with some variable that could affect this relationship (Khademi et al., 2015). According to Hobbs and Kebir (2007), it is truly a non-destructive technique, as it uses mechanical waves without any damage to the concrete element being tested. UPV can be reasonably reliable, accurate and direct applicable in situ alternative for concrete characterization. Moreover, UPV test gives easier and economic determination of variation in compressive strength over time during the construction of some of special structures, where the early compressive strength is essential (Haach et al., 2015). The procedure for UPV test is according to BS EN 12504-4 (2004). Generally, the speed of ultrasonic pulse traveling in a solid material depends on the elastic properties and density of the specimen. Concrete cubes of 100mm are tested at 7, 14 and 28 days. The apparatus is shown in Figure 3.16. Before the test started, the apparatus was calibrated to establish a zero reading, since the displayed measurement is influenced by a time delay due to both transmission of the pulse through the transducers material and transmission of electrical signal along the transducer cables. The time delay adjustment was performed, while the transducers were coupled to the opposite ends of a reference bar for which the transit time was accurately known (bar with transit time 25.2 µs was used). The velocity of the ultrasonic pulse through the concrete is a result of the time taken by the pulse to travel through the hardened cement paste and the aggregate. UPV is then calculated using Equation (3.10) and this data can be used to establish to predict the quality of concrete as given in Table 3.9.

$$v = \frac{L}{T} \qquad (3.10)$$

Where, v = ultrasonic pulse velocity (km/sec)

L = length of specimen (mm)

T = time taken to travel from transmitter to the receiver (μsec)

Table 3.9: Suggested quality criteria for concrete (BS EN 12504-4)

Pulse velocity (*km/sec*)	Concrete quality (grading)
Above 4.0	Very good
3.5-4.0	Good
3.0-3.5	Medium
Below 3.0	Poor

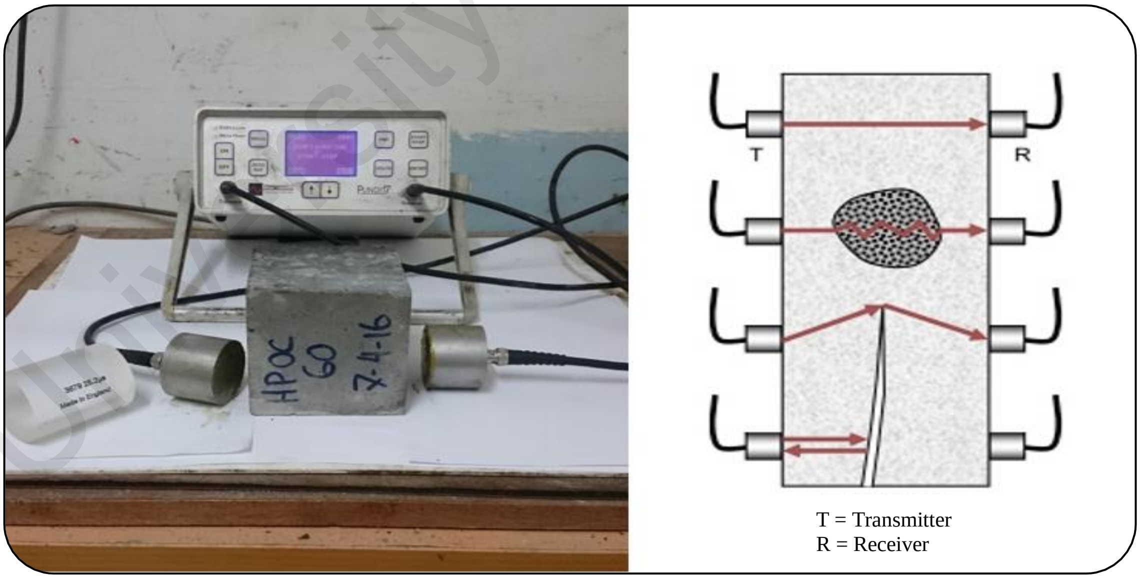


Figure 3.23: Ultrasonic pulse velocity test

3.3.6.6 Static Modulus of Elasticity

Modulus of elasticity (MOE) was determined according to BS EN 12390-13 (2013) on the cylinder specimens of (150mm dia.× 300mm length). The MOE was determined at ages of 28, 90 and 180 days. The specimen, with the strain measuring apparatus attached axially, was placed centrally in the ELE compression testing machine as shown in Figure 3.17. A basic stress (σ_b) of 0.5 N/mm^2 is applied and the strain gauge reading is recorded. The stress is constantly increased with 0.6 N/mm^2.s^{-1} until the upper loading stress equaled one-third of the cylinder compressive strength reading (σ_a), and the strain gauge reading is taken. The cylinder compressive strength (f_{cy}) is estimated based on the compressive strength of the cube (f_{cu}) by using Equation (3.11).

$$f_{cy} = 0.8 \times f_{cu} \tag{3.11}$$

The static modulus of elasticity (N/mm^2) is calculated as follows:

$$\text{MOE} = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\sigma_a - \sigma_b}{\varepsilon_a - \varepsilon_b} \tag{3.12}$$

Where σ_a = upper loading ($\sigma_a = {}^{f_{cy}}\!/_{3}$) (N/mm^2)

σ_b = basic stress (0.5 N/mm^2)

ε_a = strain under upper loading stress

ε_b = strain under basic stress

Figure 3.24: Modulus of elasticity test

3.3.6.7 Drying Shrinkage

Normally, concrete shrinkage results from the use of mixing water to provide workability. About half of the water in concrete is provided for workability and is in excess of that there is a need for hydration of the cement. Evaporation of the excess water after placement leads to capillarity in concrete. The capillaries and air voids, along with micro cracks, join to form shrinkage crack in the hardened mass. Reduction in the formation of capillaries, large voids, and shrinkage cracks will lead to reduction in the permeability and corrosion of the reinforcing steel. Demountable mechanical strain gauge (DEMEC) with a precision of 1 μm was used to monitor the total linear shrinkage. The DEMEC was placed over two steel studs at 200 mm gauge length, which had been glued on to the three as cast surfaces as shown in Figure 3.17. The test method involves measuring the length change of ($100\text{mm} \times 100\text{mm} \times 300\text{mm}$) concrete prism. The specimens were exposed to uncontrolled laboratory conditions with humidity ranging between 65% - 85% and temperature ranging between 26˚C - 35˚C. The dry shrinkage was determined by taking the average of nine sets of readings measured from three specimens. The development of the shrinkage strains with drying period up to 180 days under initial water curing condition of 7 days was monitored.

Figure 3.25: Scheme for measuring the shrinkage of concrete

3.3.6.8 Water Absorption

Water absorption is the process whereby water enters and tends to fill the pores in a porous solid body like the component of concrete. The water absorption is usually more significant at the surface layer than at the core of concrete due to strong capillary action. The rate of absorption of the dry concrete surface can be used to predict the concrete durability. Water is the most common liquid, which the concrete comes in contact. Therefore, the absorption of water is widely used to show the absorption capacity of concrete. It can be determined based on the increase in mass of a concrete sample resulting from the ingress of water into its pores. The water absorption in this study was carried out according to BS 1881 1983: Part 122. At the ages of 7, 28, 90 and 180 days of water curing, 100mm cube specimen was placed in an oven at temperature of 100±5˚C for 48 hours. The specimen is taken out and leftover to cool to the room temperature. Then the water absorption is calculated after 72 hours of submerging the specimen in water by using the following equation:

$$\text{Water Absorption (\%)} = \frac{\text{B}-\text{A}}{\text{A}} \times 100 \qquad (3.13)$$

Where, A = mass of oven-dried the specimen

B = mass of surface-dry sample after immersion

3.3.6.9 Chloride Permeability

The estimation of chloride ions diffusivity through a concrete can give data on the permeability performance of concrete. A lower chloride permeability is essential to achieve durable concrete structure. Rapid chloride permeability test (RCPT) is performed by monitoring the amount of electrical current that flow thorough a sample of concrete, which is typically cut as a slice of a core or cylinder. According to ASTM C1202, concrete specimen of 50 mm thick and 100 mm diameter as shown in Figure 3.26. The specimen is placed in a vacuum chamber for 3 hours then vacuum saturated for 1 more hour and left to soak in water for 18 hours. The specimen is then placed in the test device as presented in Figure 3.18. A reservoir is filled with 3.0 % NaCl solution, while another reservoir is filled with 0.3 M NaOH solution. The specimen is then subjected to a 60 V applied DC voltage for 6 hours by using the apparatus shown in Figure 3.27. The current that passes through the specimen during the test indicates the movement of all the ions in the pore solution. Based on the charge that passes through the sample, a qualitative rating is made of the concrete permeability. The total charge that passed is determined and this is used to rate the concrete according to the criteria given in Table 3.10.

Table 3.10: RCPT ratings (per ASTM C1202)

Charge Passed (*coulombs*)	**Chloride Ion Penetrability**
> 4,000 High	High (H)
2,000-4,000 Moderate	Moderate (M)
1,000-2,000 Low	Low (L)
100-1,000 Very Low	Very Low (V.L)

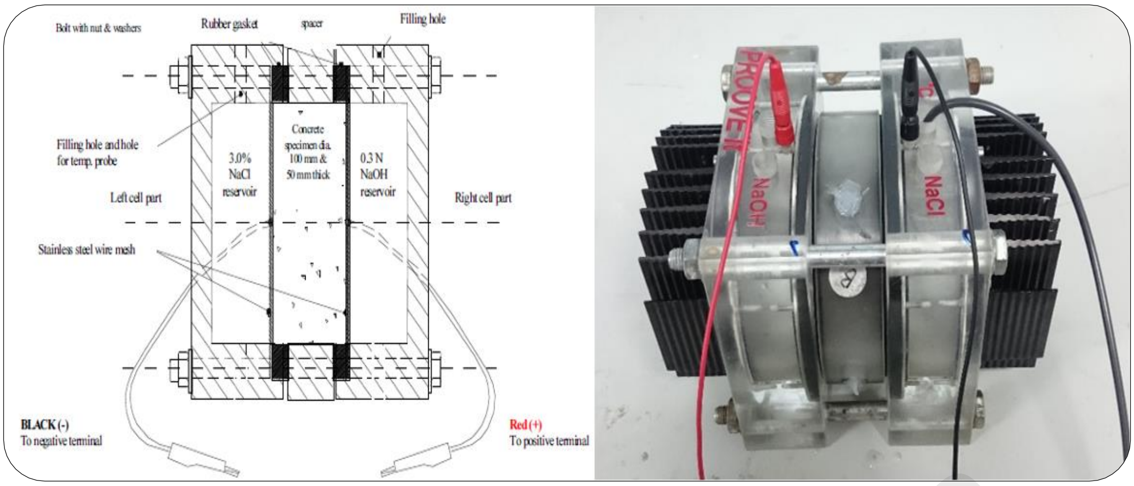


Figure 3.26: Placing the specimen in the device

Figure 3.27: Concrete specimens and test set up (ASTM C1202)

3.4 Cost Effective

The study was designed to analyze the cost comparison between the conventional and POC concrete. A cost comparison was made taking into consideration the current market cost of materials. The market price of all the materials used in this study are presented in Table 3.11, all the material prices were obtained at the same period of time to ensure consistency in the cost evaluation. POC is available in very low of cost and most of them are available without any cost involved, the values of POC were obtained though inclusion of cost of transportation, preparations and labour charges. The cost of each mixture was calculated by integrating the mix design of concrete into the current cost of materials. Engineering Economical Index (ECI) system was adopted in this study to evaluate the cost effectiveness to the mechanical properties of POC concrete mixes. The cost was calculated for the control mix, this would serve as a benchmark to determine the best mix that could be used to maximize the economic and hardened concrete quality. Engineering Economical Index (ECI) values are calculated using the following Equation:

$$\text{Engineering Economical Index } (ECI) = \frac{\text{Structural efficiency at 28 days}}{\text{Cost of the concrete mix}} \tag{3.11}$$

Table 3.11: Unit cost of materials by weight

Materials	Cost (*RM/Kg*)
Cement (OPC)	0.44
Silica fume (SF)	1.22
Granite coarse	0.05
River sand	0.08
Silica sand	0.22
POC coarse	0.02
POC fine	0.02
POC powder	0.02

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

The effect of different replacement levels of coarse and fine aggregate with POC on fresh and hardened properties of concrete are presented and discussed in this chapter. The experimental test results obtained for all the mixes of normal and high strength concretes are presented, accompanied by an extensive discussion. The discussion is based on the analysis of all the data obtained from the experiments.

4.2 Material Characterization

4.2.1 Aggregates

The physical characteristics for all aggregates used in this study are presented in Table 4.1. Based on the physical properties, POC falls within the criteria for structural lightweight aggregate. According to ASTM C 330 (2005), aggregates with specific gravity lower than 2.2 and bulk density less than 1200 kg/m^3 are classified as LWA. Chen et al. (1999) reported that LWA have a density significantly lower than conventional aggregate, ranging from 560 to 1120 kg/m^3. The unit weight of POC aggregates are approximately 25% lighter than river sand and 48% lighter than crushed granite stone. However, ACV of the coarse aggregates show that POC is weaker in strength compared to the conventional aggregate. Furthermore, it is observed that the water absorption of POC is higher than that of the natural aggregates. Ahmad et al., (2007) reported that POC aggregate is a porous material and will absorb huge amounts of water compared to the NWA. The high water absorption of POC aggregate can be valuable for the resultant hardened concrete. Hossain and Khandaker (2004) reported that LWA have higher water absorption capacity than the conventional aggregates. Consequently, in the early age of hydration, as reported by Al-Khaiat et al. (1998), the effect of poor curing on porous lightweight concrete aggregate is minimal as compared to conventional concrete aggregates. This condition is a result of the additional water absorbed and internally stored in the LWA. Thus, hardened concrete benefits from the water absorption capacity of the POC. The benefit of using POC as LWA is the reduced dead load of concrete structures without much loss in the strength of the structure. This condition is possible because lightweight concrete can reduce the dead load by as much as 35% and still provide the structural strength (Roslli et al., 2002). Studies have reported that LWC improves thermal and acoustic insulation and fire resistance, makes construction easier, and reduces self-weight (Mun, 2007).

Table 4.1: Physical characteristics of the aggregates

Properties	**Aggregates**				
	Fine Aggregate			Coarse Aggregates	
	River Sand	Silica Sand	POC Fine	Granite	POC
Aggregate Size (mm) (NC)	< 4.75	-	<4.75	4.75–14	4.75–14
Aggregate Size (mm) (HSC)	-	< 4.75	<4.75	4.75–10	4.75–10
Specific Gravity (SSD)	2.62	2.69	2.15	2.65	1.73
Water Absorption (%)	1.12	1.41	5.75	0.59	4.35
Moisture Content (%)	0.08	0.08	0.11	0.28	0.08
Aggregate Crushing Value (%)	-	-	-	17.93	56.44
Bulk Density (kg/m^3)	1268	1301	811	1452	732

Figure 4.1 and 4.2 depict the sieve analysis grading curve for the river sand, POC fine, granite coarse and POC coarse that were used in this study. The aggregates satisfied the parameters and fell within the range of well-graded aggregate as stipulated in BS882:1992. This result indicates that this waste material is suitable for the replacement of natural aggregates for structural application. Kanadasan et al. (2015b) reported that the similarity of the particle size distribution and the grading features of the sand and POC fine indicate the suitability of POC fine substitution. Mannan et al. (2010) mentioned that POC is available as both fine and coarse aggregate and is a well-graded and promising material for use in concrete work.

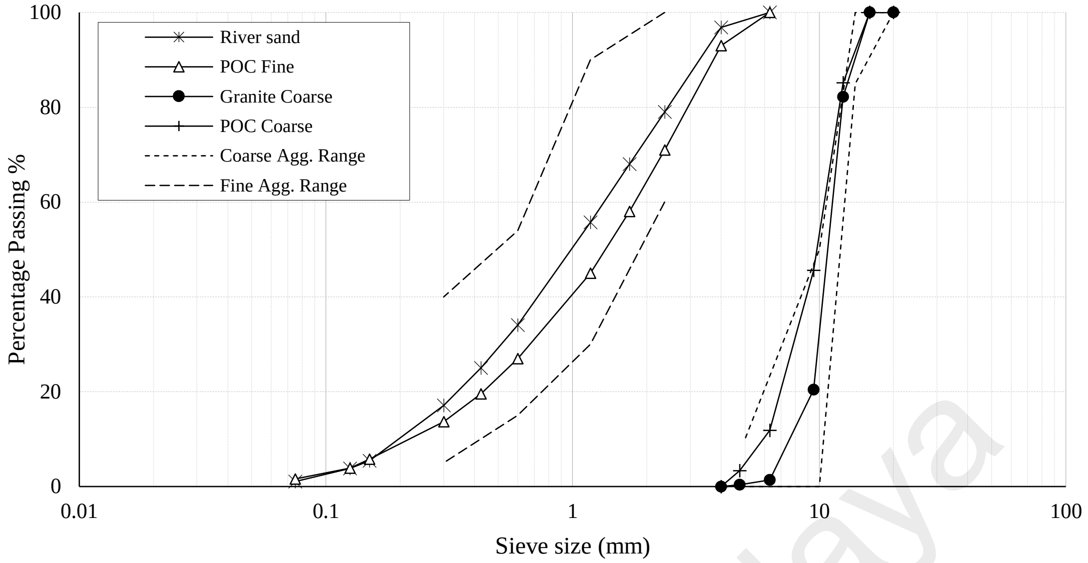


Figure 4.1: Sieve analysis grading of NC aggregates

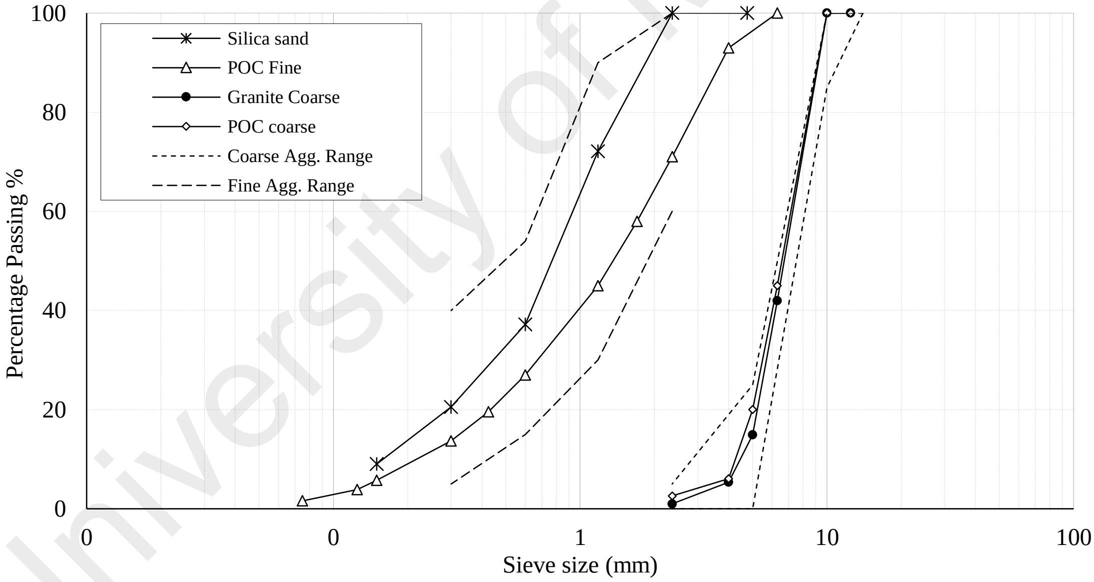


Figure 4.2: Sieve analysis grading of HSC aggregates

4.3 Normal Concrete

4.3.1 Direct Replacement

4.3.1.1 Workability

The consistency of the concrete was accessed by the measure of slump in this study. Figure 4.3 shows the slump results of POC and POCF concrete mixes. During visual observation, the mixes of POC concretes were found to be somewhat harsher and less cohesive than the corresponding conventional concrete. The workability of the mixes was affected by incorporating POC coarse. Increasing the substitution ratio of POC decreases the workability of the mix. The reduction of the workability is attributed to the particle shape and rough surface, as well as the sharp broken edges of POC. Ferraris et al. (2001), concluded that workability of a mix is a function of the aggregate characteristics, the paste volume, and the rheology of the paste. Abdullahi et al. (2008) reported a slump value for NWC of 70 mm with a compressive strength of 40 MPa, while the slump of LWC using POC aggregates varied from 0 to 50 mm. The irregular shape of POC has resulted in higher surface area increasing the demand for extra paste volume to ensure good workability. With a greater replacement rate of POC coarse, the surface area of the aggregates generally increased compared to the control mixes. As such, increasing the demand of paste to lubricate the aggregates. The required amount of paste to coat and give extra lubrication to the POC aggregate should be determined for different substitution levels. Meanwhile, the replacement of natural sand with POC fine aggregate did not affect the workability of the mixtures, and the values obtained was within the targeted slump range of 100±25 mm as shown in Figure 4.3. The presence of smaller voids compared to that of the aggregate size for fine POC reduces the need for extra lubrication to achieve a similar workability to that of control mixes. Furthermore, the fineness modulus of sand was close to that of fine POC as observed from the grading curve, thus providing comparable workability to non-POC mixes.

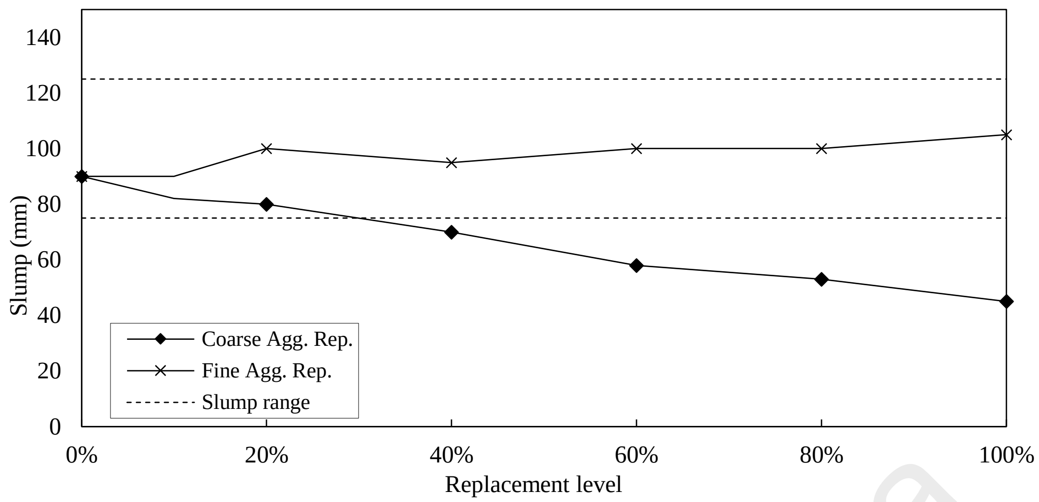


Figure 4.3: Slump results for the replacing of coarse and fine aggregate

4.3.1.2 Fresh density

According to the physical properties of aggregate, the unit weight of POC is approximately 37% lighter than river sand and 43% lighter than crushed granite stone. The concrete density of the mixes was expected to be lower than that of the control mix with conventional aggregates. Figure 4.4 shows the effect of aggregates replacement i.e. fine and coarse with POC on the fresh density of concrete. The unit weight of concrete with POC aggregates is inversely proportional to the replacement level. Increasing the amount of POC in the mix reduces the unit weight of the concrete. Fresh density of POC and POCF concretes were in the range of 2032 - 2273 kg/m^3. The maximum reduction was at full replacement, which registered a value of 14% and 5% lower than that of control concrete i.e. 2379 kg/m^3 for coarse and fine aggregate replacement, respectively. This is similar to study by Kanadasan et al. (2015b), they reported that an approximate reduction of about 7% can be observed when the mortar specimens are fully replaced with POC. Some researchers studied the use of POC as both fine and coarse aggregates and reported that the density of POC concrete ranged between 1440 and 1850 kg/m3 which is ranging between 23% to 40% lower than the density of NWC (Kanadasan et al., 2014a). The existence of the large number of voids and pores contributes significantly to the light nature of POC aggregate. Kanadasan and Razak (2015) reported that the lower unit weight coupled with the porous nature of the POC aggregate directly results in a lower mass per volume of POC self-compacting concrete. Their results revealed that full replacement of POC produces concrete with a density less than 2000 kg/m^3, which is approximately 16% lower than the control mix.

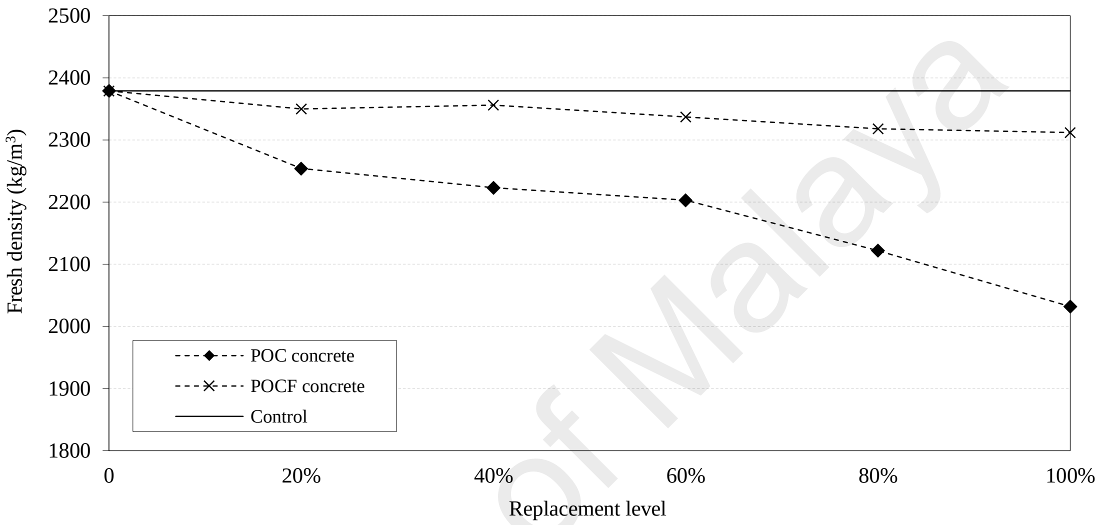


Figure 4.4: Fresh density of POC and POCF concrete mixes

4.3.1.3 Hardened Density

The hardened density of POC and POCF concrete mixes at 28 days was in the range of 2377 to 2065 kg/m^3 as shown in Figure 4.5. The maximum reduction was at full replacement of POC coarse aggregate. The density was dropped by 14% and 4% for coarse and fine aggregate replacement, respectively, compared to the control mix. Similarly, the research of Rashid et al. (2012) on lightweight aggregates revealed that crushed clay brick waste has a bulk density that is 45% lesser than the conventional coarse aggregate. The study also reported that the low bulk density reduced the hardened density by 13.4% at full replacement of the conventional coarse aggregate with crushed clay brick waste. Mannan et al. (2010) stated that the density of POC LWC fell in the range of 1800 -2000 kg/m^3. Ahmad et al., (2007) used the same materials but replaced the cement by weight with 10% fly ash. They reported the density range as 1880-2030 kg/m^3 which is approximately 16-22% lower than the density of the NWC. Table 4.2 shows the coefficient of variation (COV) of six samples for the hardened density of the POC concrete specimens. The COV of the values obtained does not exceed 1.05%, suggesting that POC exhibits consistent lightweight concrete properties for mass production.

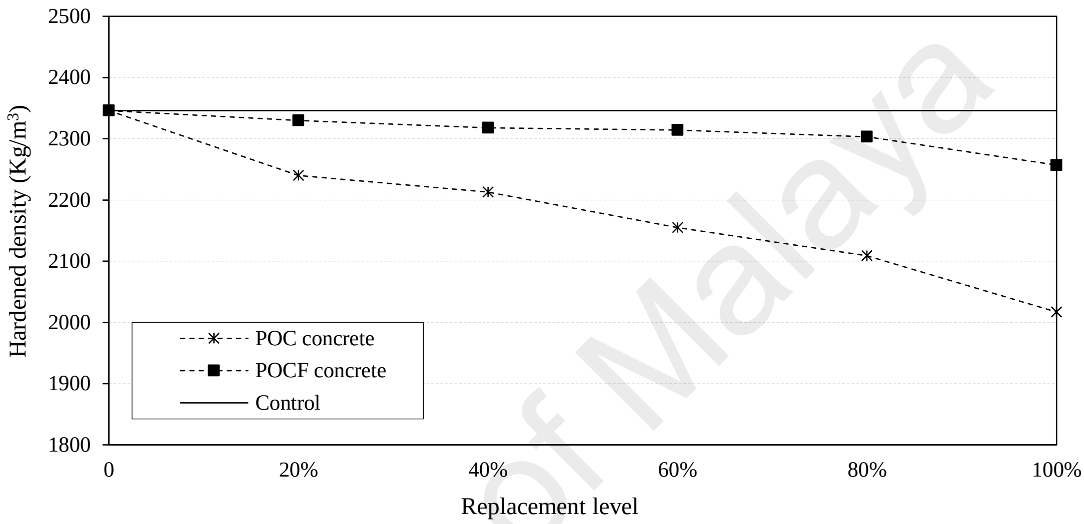


Figure 4.5: Hardened density of POC and POCF concrete mixes

Table 4.2: Coefficient of variation of density and compressive strength at 28 days

Replacement level (%)	Compressive strength (MPa)	Hardened Density (kg/m^3)
Control (M0)	47.41 (3.98)	2395 (0.63)
Replacement of coarse aggregate (POC series)		
POC20	39.45 (5.43)	2294 (0.88)
POC40	38.43 (4.04)	2268 (1.03)
POC60	38.09 (3.03)	2191 (1.04)
POC80	37.17 (2.65)	2143 (0.83)
POC100	33.01 (4.3)	2074 (0.68)
Replacement of fine aggregate (POCF series)		
POCF20	45.31 (1.69)	2380 (0.64)
POCF40	47.34 (3.9)	2346 (0.66)
POCF60	47.03 (4.18)	2335 (0.96)
POCF80	49.81 (4.64)	2340 (0.97)
POCF100	44.96 (3.27)	2313 (0.70)

*the values in parentheses represents the coefficient of variation (COV %)

4.3.1.4 Compressive Strength

The compressive strength was determined in accordance with BS EN 12390-3 (2009). In general, there is a reduction in compressive strength when POC coarse aggregate is used. The concrete strength becomes lower when higher content of conventional aggregate is substituted by POC. Figure 4.6 shows the results of the compressive strength test for each replacement level of coarse aggregate with POC at 3, 7, 14 and 28 days. At 28 days the compressive strength of POC concretes ranged from 33 to 39.45 MPa. The maximum reduction was at full replacement of POC, which is approximately 30% lower than the control concrete as shown in Figure 4.7. This is equivalent to concrete grade 25 according to the mix design. This reduction is attributed to the high number of voids in POC coarse. The strength and stiffness of POC were much lower than the conventional coarse aggregate due to its porosity, which significantly affects the strength carrying capacity of concrete. The empty voids or pores within the internal structure of POC resulted in a reduction of the concrete density, as such decrease the load carrying capacity of the hardened concrete mix as shown in Figure 4.8. This is also attributed to the fact that less matrix is available to fill up the pores within the POC aggregates leading to a higher total porosity in the concrete. It can be observed clearly in Figure 4.10 that the presence of significant number of voids or empty zones within the aggregate for POC compared to the control concrete. The reduction in strength can also be explained by the aggregate crushing value (ACV) of POC. As mentioned in an earlier research by Kanadasan and Razak (2014b), POC coarse produced a crushing value that is three times higher than normal granite. This observation agrees with a study by Abdullahi et al. (2008) on investigation the influence of incorporating POC as coarse aggregate replacement. Their results revealed that the compressive strength of the mixes containing 0%, 25%, 50%, 75% and 100% POC were 40, 42, 35, 30 and 26 MPa, respectively. Kanadasan and Razak (2014b) reported that despite completely replacing granite coarse aggregate with POC, the strength dropped by approximately 30% at 28 days. This is also corroborates with the results of the study by Rashid et al. (2012) on the utilization of LWA from waste material using crushed clay bricks as coarse aggregate replacement. The study reported that the replacement resulted in strength reduction of 9.6% and 32.9% at 50% and 100% replacement levels, respectively. Meanwhile, the replacement of fine aggregate with POC had insignificant effect on the compressive strength as observed in Figure 4.9. Despite full replacement of fine aggregate, the strength achieved was almost similar to that of the control concrete, indicating a comparable performance of fine POC with natural sand. POCF concretes gave higher strengths as compared to POC concretes. The significant reduction in the void ratio helps to maintain the strength, thereby making it comparable with that of normal sand. Furthermore, in smaller size fractions, POC fine and the river sand particles have similarity of packing arrangement, which helps to avoid substantial formation of voids. Table 4.3 indicates the COV of six samples for the compressive strength of POC and POCF concretes. The values obtained are less than 5.5%, indicating good consistency of POC in replacing natural aggregates i.e. fine and coarse in concrete considering the strength properties. The results for POC fine inclusions met the required strength for concrete grade 40 with no deterioration effects on the compressive strength. Thus, POC fine can be utilized as a direct replacement of natural sand.

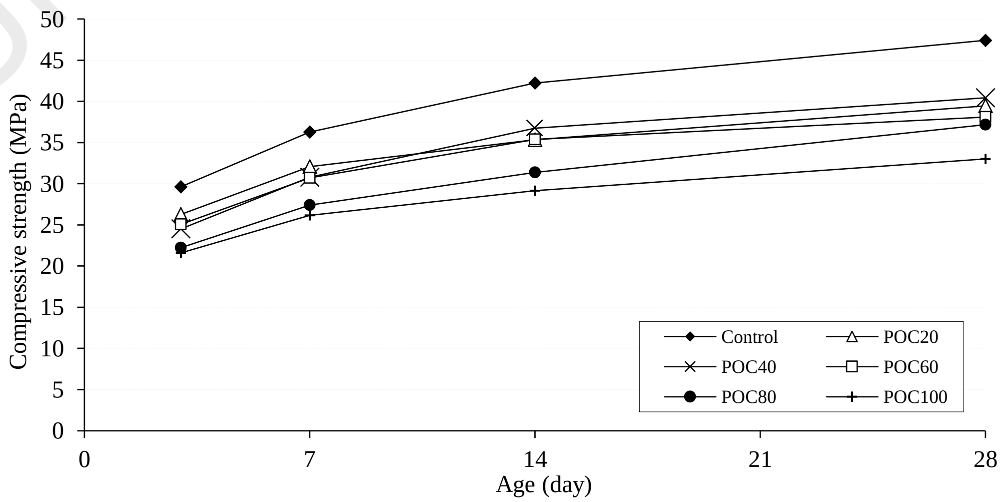


Figure 4.6: Strength development of POC concretes

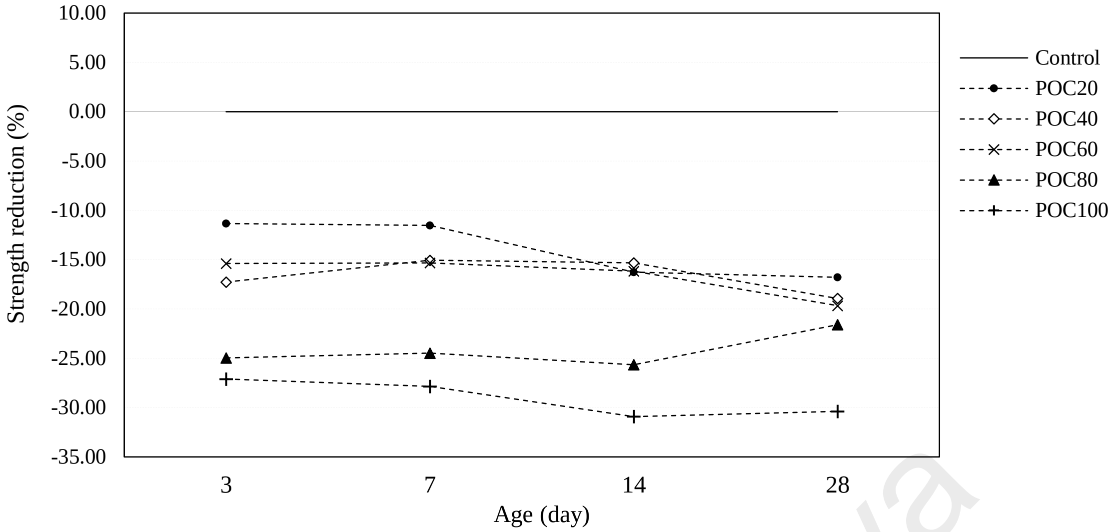


Figure 4.7: Compressive strength reduction of POC concrete mixes

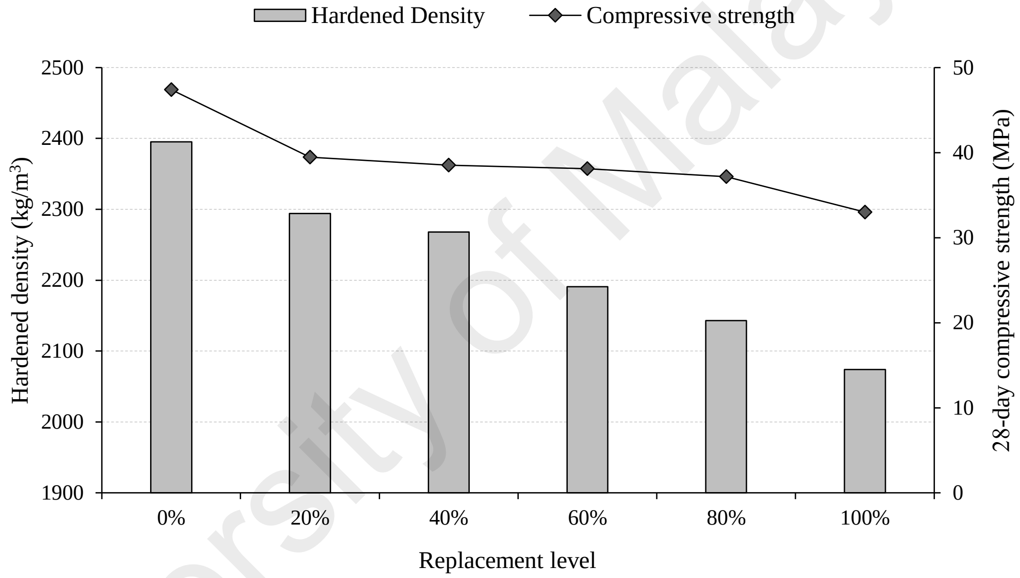


Figure 4.8: POC coarse, hardened density and compressive strength relationship

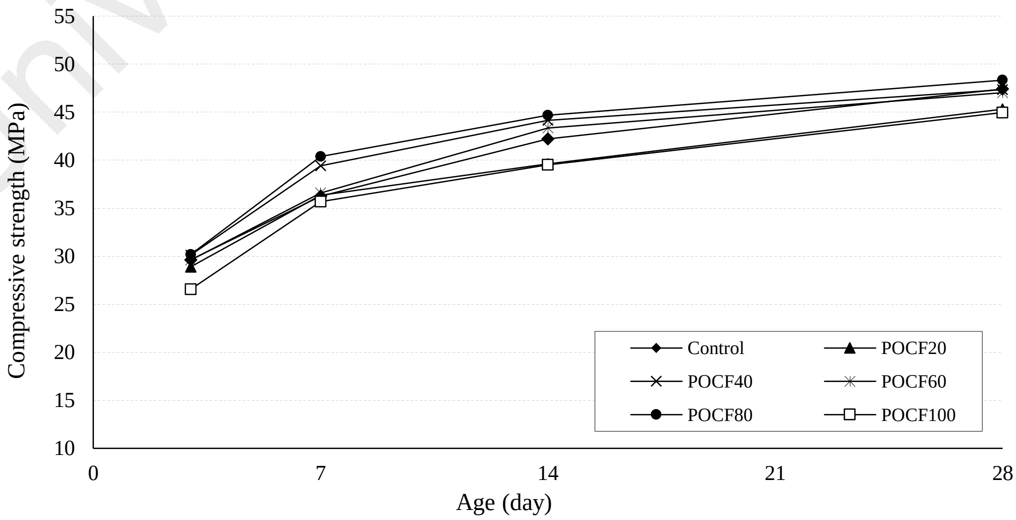


Figure 4.9: Strength development of POCF concrete mixes

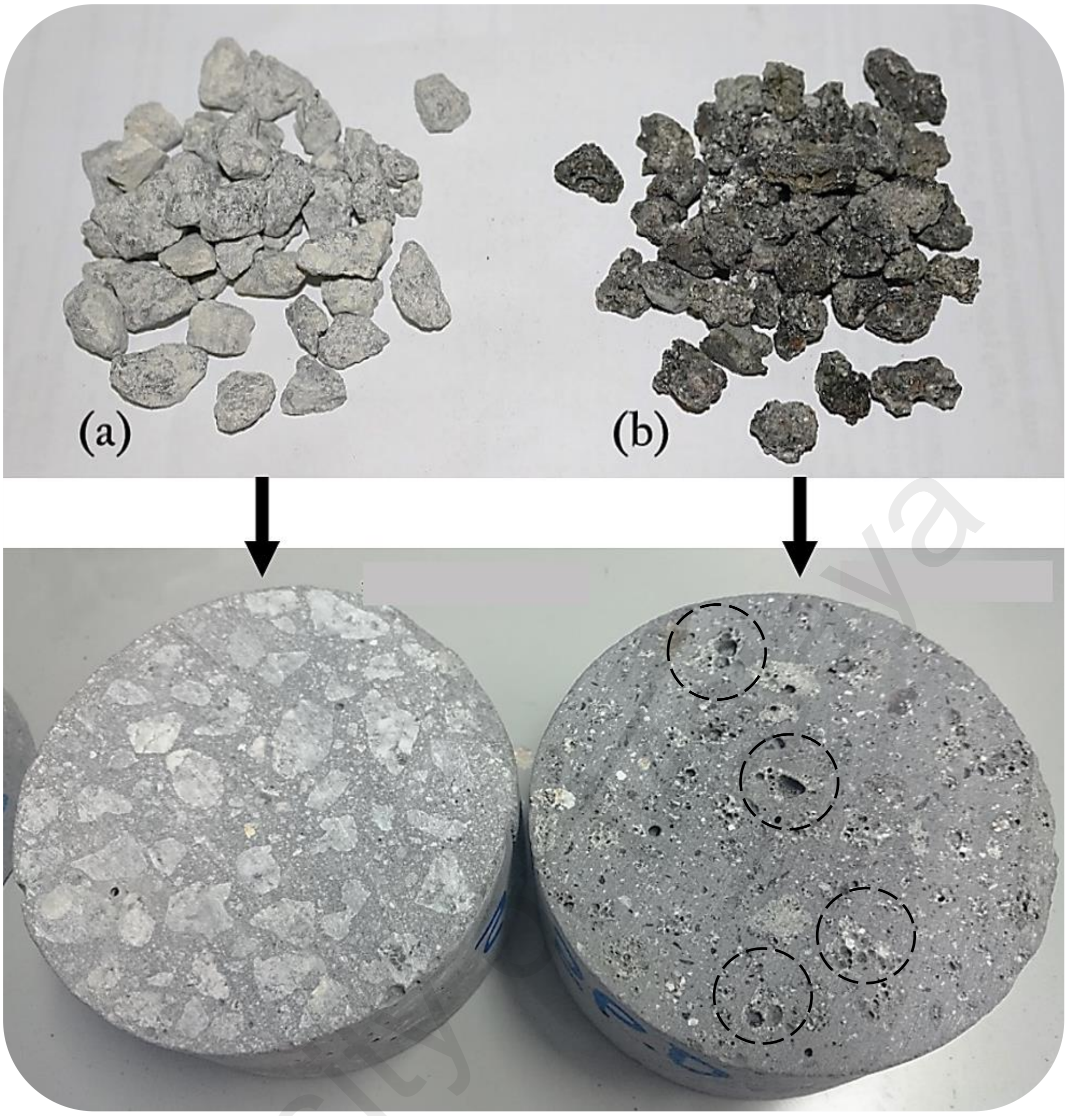


Figure 4.10: Difference in porosity of concrete: (a) granite; (b) POC

4.3.1.5 Ultrasonic Pulse Velocity (UPV)

UPV values provide substantial information on pulse transfer rate in concrete specimens, which is indirectly related to the porosity of the concrete. Pulses are not transmitted through large air voids in a material. Therefore, if such a void lies directly in the pulse path the instrument will indicate the time taken by the pulse that circumvents the void by the quickest route. Thus, it is possible to detect large voids when a grid of pulse velocity measurements is made over a region in which these voids are located. It is vital to evaluate the UPV values in this study especially as it provides the denseness of the concrete in myriad of the POC incorporation. Figure 4.11 depicts the UPV values at various POC substitution ratios. At 28 days, the UPV values are in the range between 4.4-5.2 km/sec. The highly porous of POC aggregates affects the wave propagation across specimens. A decreasing pattern of UPV was observed as the POC incorporation increased. In the lower coarse replacement with POC, the pulse transfer is enhanced because of the solid nature of gravel, which helps to transport the pulse quickly. The lower void content increases the denseness of the concrete to produce faster pulse transfer. Meanwhile, the empty voids within and between POC aggregates reduce the velocity of the pulse because of the impeding effect of air. However, researchers have rated UPV values between 3.66 - 4.57 km/s as a good quality concrete (Hwang et al., 2012). All UPV values in this study surpassed the minimum threshold value for good quality concrete as shown in Figure 4.11. Furthermore, in later ages the UPV values are even more favorable. The trend of increase in the UPV with the increasing age of concrete could be attributed to the bonding between the mortar and aggregate; this enables the concrete to enhance its strength with reduced pores in the solid skeleton of concrete (Ahmmad et al., 2016). Meanwhile, no significant variation of UPV values was observed for POCF concretes. The smaller grain size of the POC fine that is similar to the natural aggregate does not have a significant impact to strength due to the smaller void-to-aggregate size ratio within the POC fine, indicating similarity in the values of UPV and satisfactory performance when replaced. In addition to the above-mentioned points, it is important to discuss the correlation between UPV values and the compressive strength. Although there is no unique correlation with UPV and the compressive strength of the concrete (Bogas et al., 2013). However, based on the experimental results, Bogas et al. (2013) gave the relationship between UPV value in concrete (V_c) and its compressive strength (fc) as:

$$fc = ae^{bV_c} \tag{4.1}$$

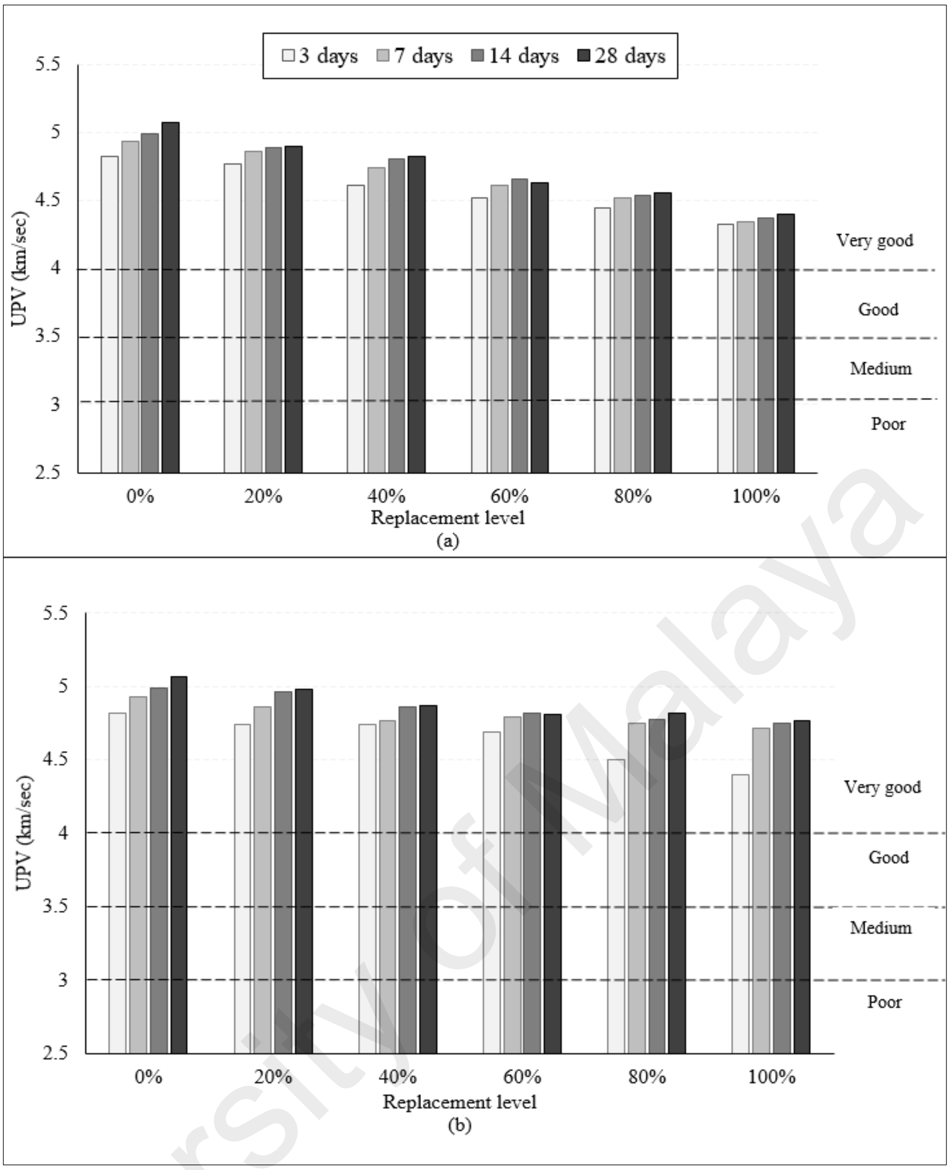


Figure 4.11: UPV values (a) POC concretes (b) POCF concrete mixes

Considering the heterogeneous nature of concrete, the general relationship between UPV and compressive strength is pooled together for all results of POC and POCF concretes in Figure 4.12 at ages between 3 and 28 days. There was a very good exponential relationship between strength and UPV, with correlation coefficient of 0.78 as shown in Equation 4.2.

$$fc = 2.248\, e^{0.5958V_c} \qquad (R^2 = 0.78) \qquad (4.2)$$

The relationship determine in this study fitting the general equation (4.1) that was reported by Bogas et al. (2013) and comparable to other equations of different studies presented in Table 4.3. Thus, this equation of the relationship between UPV and the compressive strength can be established to predict the compressive strength of POC and POCF concretes based on UPV values.

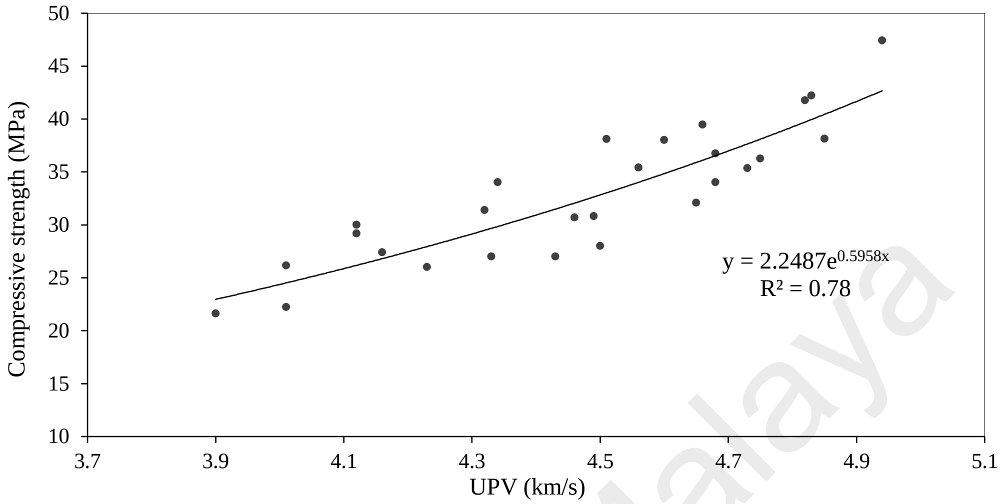


Figure 4.12: UPV and the compressive strength relationship

Table 4.3: Relationship between compressive strength and UPV

Relationship	R^2	Reference	Equation No.
$f_c = 2.248\ e^{0.5958V_c}$	0.78	This study (NC)	(4.3)
$f_c = 1.19\ e^{0.715V_c}$	0.59	(Nash't et al., 2005)	(4.4)
$f_c = 1.146\ e^{0.77V_c}$	0.80	(Turgut, 2004)	(4.5)
$f_c = 3.38e^{0.62V_c}$	0.61	(Bogas et al., 2013)	(4.6)
$f_c = 0.32e^{0.9895V_c}$	0.51	(Trtnik et al., 2009)	(4.7)

Where f_c is the compressive strength and V_c is UPV value of concrete

4.3.2 Direct Replacement with POCP

4.3.2.1 Workability

It is obvious from Figure 4.13 that the workability of POCP concretes was improved when addition of POCP was used as filler material to fill up the voids due to the porosity of POC. The observed improvement in workability can be partly attributed to the higher paste volume. POCP helps to coat the particles of POC coarse, filling the gaps between the aggregates, thereby providing a better chance for aggregate lubrication. Ferraris et al. (2001) have concluded that workability of a mix is a function of the aggregate characteristics, the paste volume, and the rheology of the paste. Girish et al. (2010) reported that an increase in paste volume can improve the slump flow values generally for varying water content. Mixes incorporating higher content of POC coarse tend to require higher POCP content as well as higher dosages of SP to make the mixes more cohesive and to achieve the targeted slump range of 100±25mm.

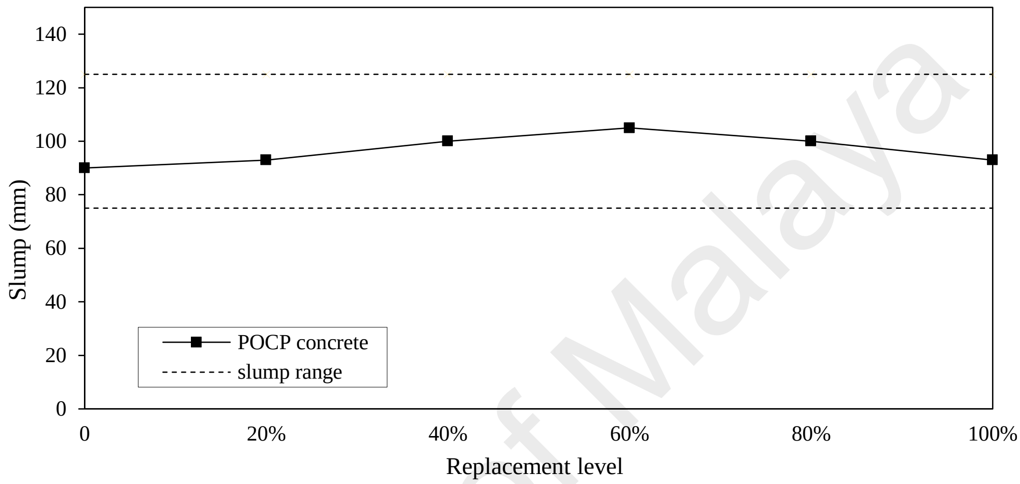


Figure 4.13: Slump values of POCP concrete mixes

4.3.2.2 Compressive Strength

It can be observed in this study that a significant reduction in compressive strength of POC concretes can be avoided for the mixes containing addition of POCP. Limbachiya (2009) reported that the use of filler material could improve the stability of such concrete mixes. Addition of POCP significantly improved the compressive strength of POC concretes by providing a sufficient amount of paste to fill up the POC voids. The influence of the POCP addition on the compressive strength of POC concrete mixes is plotted in Figure 4.14. Generally, the presence of a higher amount of paste affects the overall strength performance. At 28 days, the strength of POCP concretes ranged between 40.52-51.27 MPa. The highest compressive strength obtained was for the mix of POCP20 and it is higher than the control mix. Compared to the mixes without POCP, the strength was increased by 20% to 30%. Kanadasan and Razak (2014b) reported that the variation in paste volume for different replacement levels of POC coarse according to the PP has a significant impact on the hardened properties of SCC made with POC coarse. Figure 4.15 illustrates the development of the POCP concretes strength up to 180 days. It is obvious that the strength of POCP concretes are significantly higher compared to POC concretes at all ages. Two main factors can be associated to this strength improvement. First, POCP micro-filler effect contributed to the strength at early age because it filled the POC particles voids, resulting in improvement in the concrete overall strength. Second factor can be attributed to POCP pozzolanic reaction. The high silica dioxide content present in POCP will chemically react with the calcium hydroxide $Ca(OH)_2$ thereby forming a secondary calcium-silicate-hydrate (C-S-H). This process also effectively improve the interfacial bond between the aggregate and cement, and densifies the concrete microstructure (Lotfi et al., 2014). However, a decreasing trend of the compressive strength was found with the increase of POC coarse contents in POCP concrete mixes, this is attributed to the factors were mentioned in section 3.4.1.4.

Figure 4.16 shows the variation of relative strength, which can be defined as the ratio of the tested specimen's strength to that of control concrete at the same age. It can be seen that for all replacement levels, the maximum relative strength occurred on the 3rd day for the mix of 20% POC coarse and decreased until it reaches a relatively constant value at 56 days and beyond. At a 20% replacement of POC coarse, the compressive strength improved due to the lesser percentage of POC in the mix when compared to the other replacement levels. Therefore, the effect of ACV of POC on the compressive strength of the concrete was not pronounced. The combined effect of POCP and the low percentage replacement of POC coarse ensured that POCP20 exhibited superior properties as compared to other replacement levels. However, at the age of 28 days, the mixes with up to 80% replacement ratio of POC coarse exceeded the control strength. Meanwhile, the mix of full replacement achieved 90% of the control strength, which continued to increase with age until it becomes closer to the control strength after 90 days as shown in Figure 4.16. These results strengthen out that the inclusion of POCP is able to give tremendous contribution to the strength property of POC concretes. Thus, the finer POCP particles have better voids-filling ability, resulting in low void space that culminates in higher compressive strength. Furthermore, the increase of the compressive strength of POCP concretes is also attributed to the better bond strength between matrix and aggregate. Utilization of POC coarse had been noted to produce a dense Interfacial Transition Zone (ITZ) microstructure and improve the interaction mechanism between the aggregate and cement paste (Kanadasan et al., 2015b). Golias et al. (2012) reported that the porous LWA can play an internal curing role to provide hydration water to cementitious material and decrease the number of micro cracks in ITZ that resulted in enhanced compressive strength of concrete. Furthermore, enhanced particle packing improved fine particle distribution densifies the ITZ for POCP concretes in comparison to POC concretes.

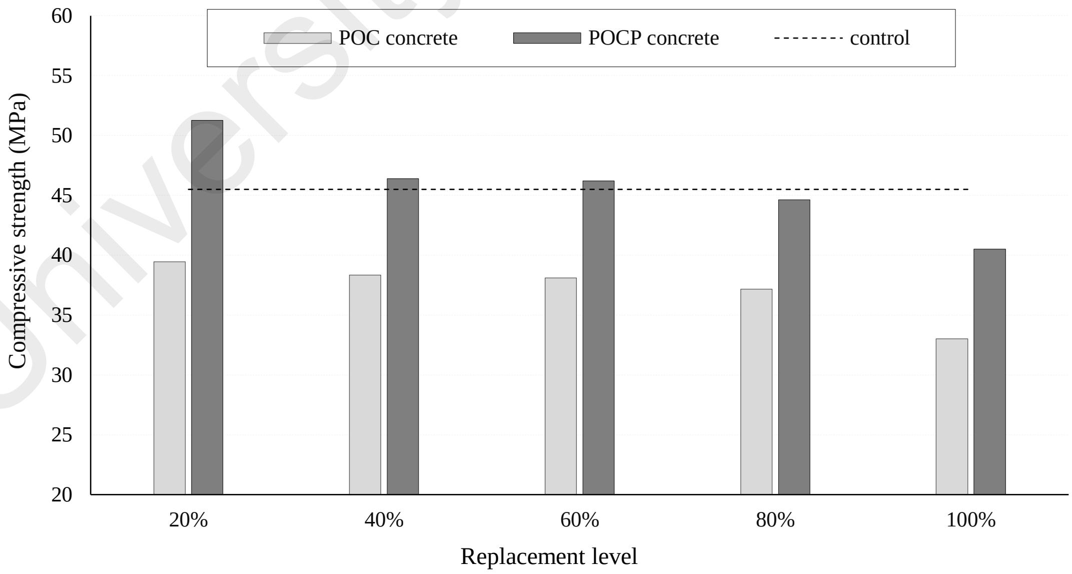


Figure 4.14: 28-day compressive strength of POC and POCP concrete mixes

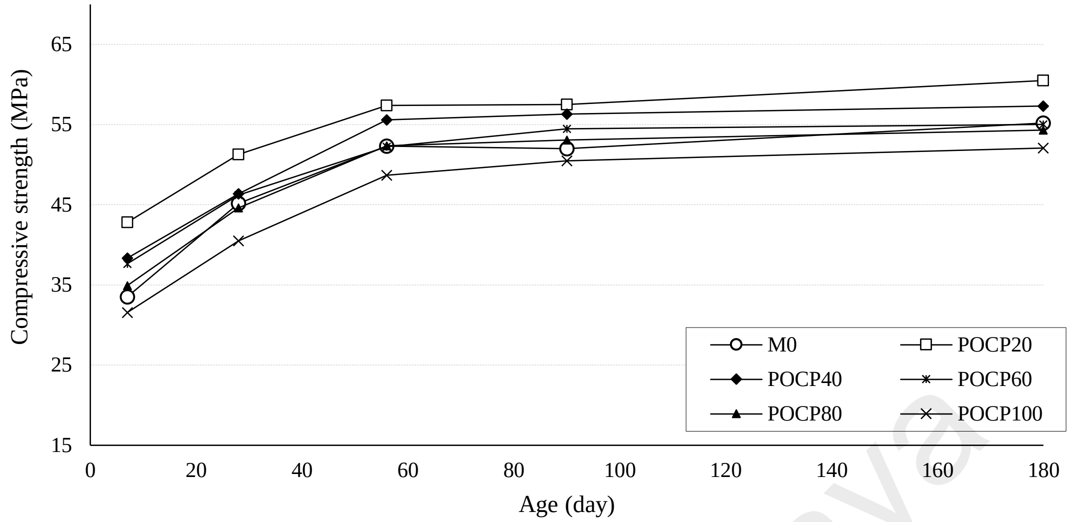


Figure 4.15: Development of POCP concrete mixes strength

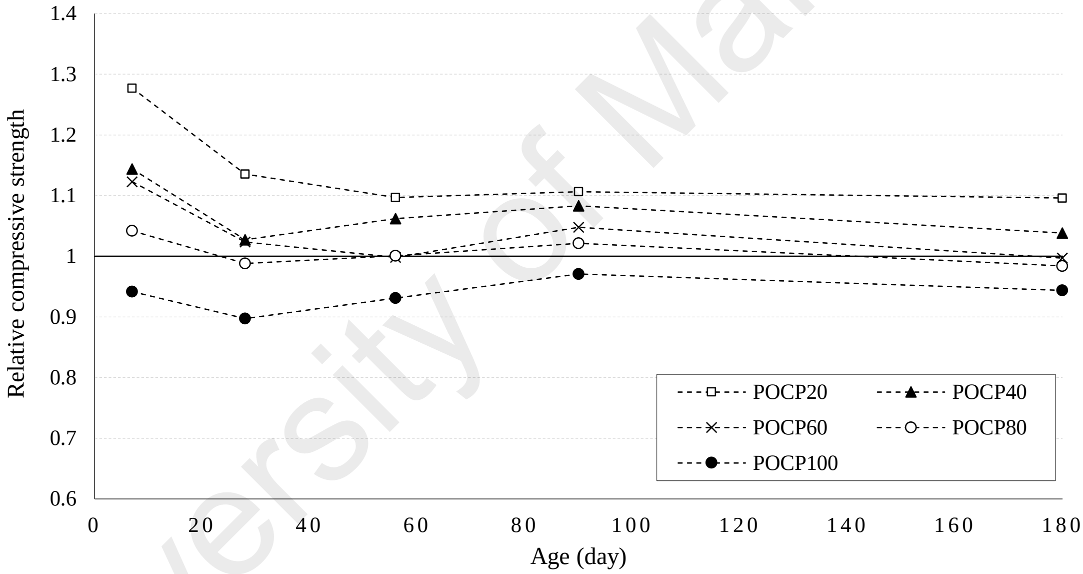


Figure 4.16: Relative compressive strength of POCP concrete mixes

4.3.2.3 Splitting Tensile Strength

Splitting tensile strength is the most frequently applied method to measure the tensile strength of concrete because of the simplicity and properly of the test. Splitting tensile strength results in this study of POC concretes generally showed a trend similar to that observed in the compressive strength. The replacement of POC with natural coarse aggregate led to a reduction in the splitting tensile property as shown in Figure 4.17. The high the contents of POC coarse the lower splitting tensile value. The 28-day splitting tensile of POC concretes was in the range of 2.61 to 3.28 MPa. The maximum reduction was at full replacement of POC which registered a value of 27% lower than the control concrete. Meanwhile, POCP concretes recorded an increase varied between 10 to 31% with respect to POC concrete mixes at the age of 28 days, the splitting tensile values was in the range of 3.23 to 3.83 MPa. The development of splitting tensile strength of POCP concrete mixes up to 90 days are presented in Figure 4.18. All the mixes had tensile strength values closer to that of control mix at different ages and no trend was found linking this property with the replacement ratio of POC. At 28 days, the maximum strength reduction of POCP concretes was at full replacement, which registered a value of 11% lower than control mix. However, it became closer to the control at the age of 90 days as shown in Figure 4.19. This small reduction can be explained by the good bond between the POC coarse and the matrix which has a significant role in tensile strength of concrete. During the visual examination of broken specimens as shown in Figure 4.20, the failure of the specimen was mainly due to the breaking of POC particles, while the bonding between the hardened cement paste and POC remained good. As such, the failure occurred through the POC coarse which is weaker compared to matrix and aggregate-matrix interface. It can be concluded that the weakest component in the concrete is the POC coarse rather than the ITZ between the aggregates and hardened cement paste.

Nevertheless, the obtained tensile strength for POCP concretes was always higher than the minimum recommended by ASTM C330 for structural lightweight concrete i.e. 2 MPa. Previous studies (Abdullah, 1996; Mannan et al., 2002; Teo et al., 2006) reported that the 28 days splitting tensile strength of LWC ranged between 1.10-2.41 MPa for moist cured concrete. In general, LWC with cube compressive strengths of 50, 40 and 30 MPa has splitting tensile strength in the range of 2.5-3.8, 2.2-3.3, and 1.8-2.7 MPa, respectively (Shafigh et al., 2010). However, the measured splitting tensile strength of POCP concretes at 28 days in this study was in the range of 3.23-3.82 MPa, which is higher than that reported in previous studies on LWC (A. Abdullah, 1996; Mannan et al., 2002; Teo et al., 2006).

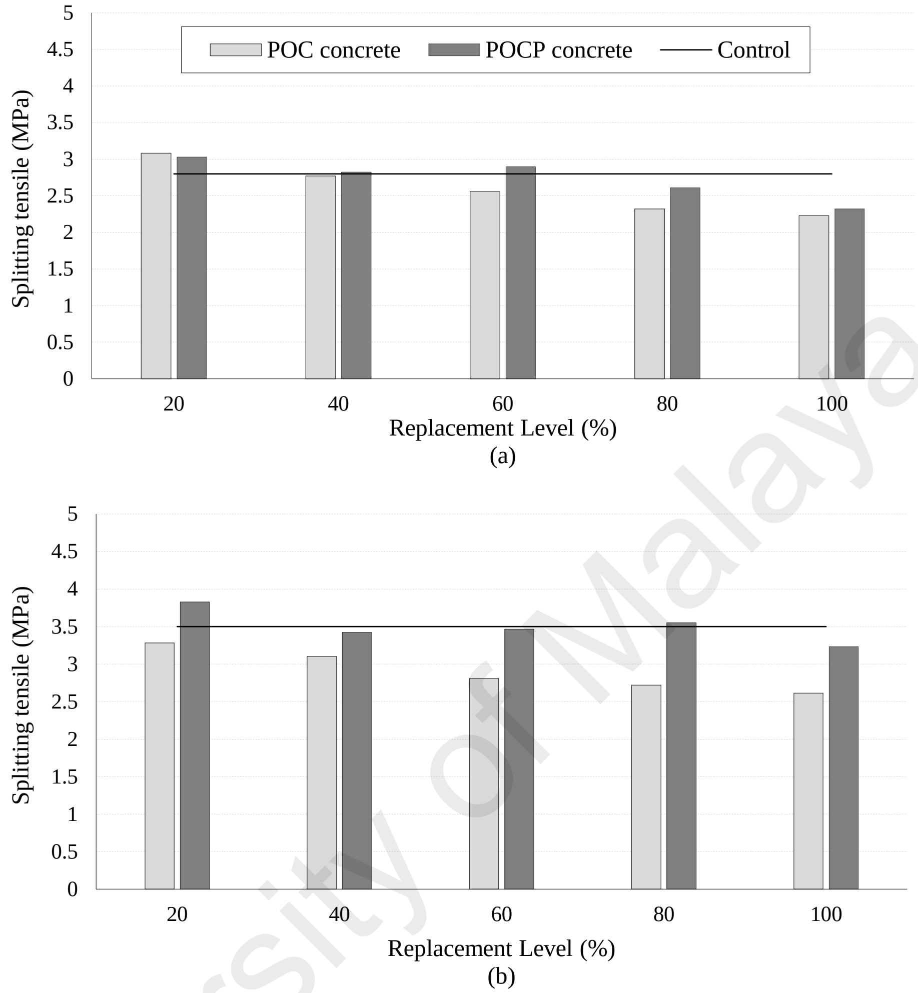


Figure 4.17: Splitting tensile (a) 7 days (b) 28 days

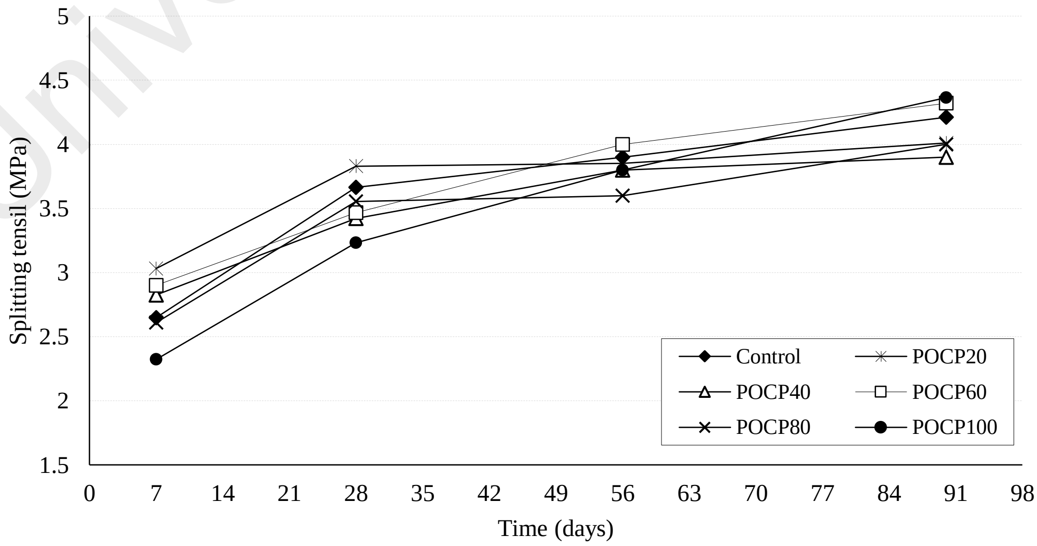


Figure 4.18: Development of splitting tensile of POCP concrete mixes

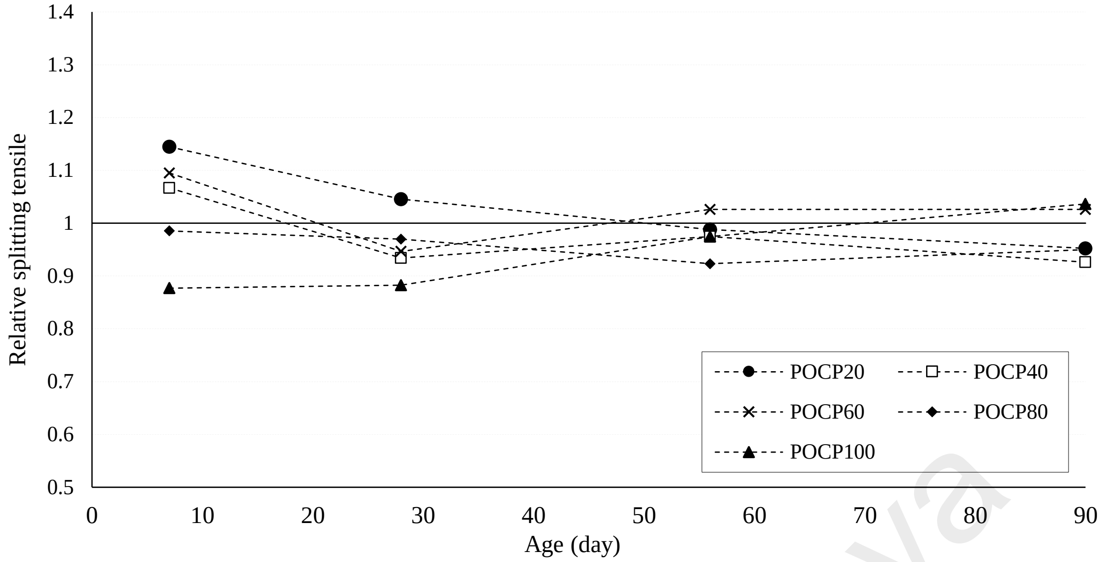


Figure 4.19: Relative splitting tensile strength of POCP concrete mixes

Figure 4.20: Splitting tensile failure

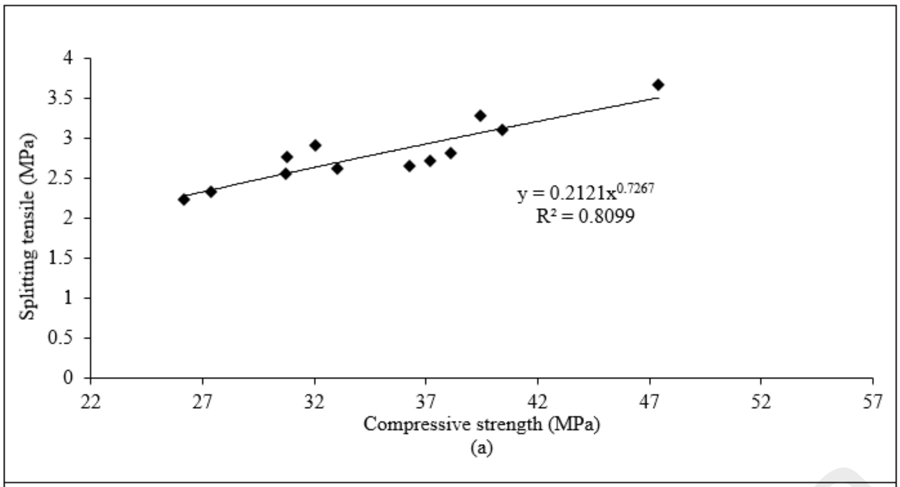
The relationships between compressive strength, flexural and splitting tensile strength of POCP concrete mixes at 28 days are presented in Table 4.4. Shafigh et al. (2012) reported that generally the splitting tensile strength for NWC is ranging between 8 to 14%

of the its compressive strength. However, the splitting/compressive strength ratio for normal weight concrete is higher compared to the lightweight concrete (Haque et al., 2004). At the age of 28 days the splitting tensile strength of POCP concretes in this study ranged from 6.8% to 8.1% of the compressive strength as shown in Table 4.4. This is similar to tensile/compressive strength ratio ranging from 6.6% to 9% of LWC made with an artificial LWA as reported by Haque et al. (2004).

Table 4.4: Flexural, splitting and compressive strength relationship at 28 days

ID	Cube Compressive Strength (MPa) f_{cu}	Flexural Strength (MPa) f_r	$\frac{f_r}{f_{cu}}$	Splitting Tensile (MPa) f_t	$\frac{f_t}{f_{cu}}$
M 0	45.16	4.422	9.79	3.663	8.11
POCP20	51.27	4.521	8.82	3.829	7.47
POCP40	46.39	4.501	9.70	3.422	7.16
POCP60	46.22	4.381	9.48	3.315	6.82
POCP80	44.63	4.800	10.76	3.553	7.96
POCP100	40.52	4.534	11.19	3.233	7.51

A parabolic relationship with correlation coefficient of 0.8 and 0.86 were observed between the 28-day compressive strength and splitting tensile of POC and POCP concretes, respectively as shown in Figure 4.21. The comparison between the splitting tensile strength predicted using various equations listed in Table 4.5 and the experimental values obtained in this study are presented in Figure 4.22. The equations of (4.8) and (4.9) were proposed based on the results of this study for POC and POCP concrete mixes, respectively. The results revealed that the predicted splitting tensile from compressive strength of POCP concretes are closer and comparable with the equations of (4.10), (4.11) and (4.14) where reported by ACI-318-11, Eurocode 4-04 and Gesoğlu et al. (2004), respectively and overestimation than the results using equations (4.12) and (4.13) where reported by Smadi and Migdady (1991) and Neville (2008), respectively.



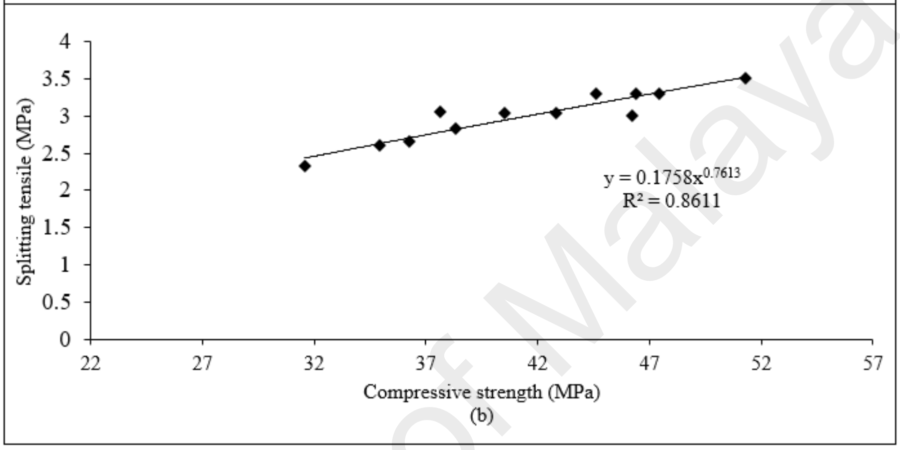


Figure 4.21: Splitting tensile and compressive strength relationship: (a) POC concretes; (b) POCP concrete mixes

Table 4.5: Practical equations for splitting tensile strength of concrete

Equation	Description	Reference	Equation NO.
$f_t = 0.21 f_{cu}^{0.73}$	POC concrete with cube compressive strength ranging between 33 to 47 MPa	This study (NC)	(4.8)
$f_t = 0.176 f_{cu}^{0.76}$	HPOC concrete with cube compressive strength ranging between 40 to 51 MPa	This study (NC)	(4.9)
$f_t = 0.53 f_{cy}^{0.5}$	ACI-318-11	ACI-318-11	(4.10)
$f_t = 0.3 f_{cy}^{0.67}$	Eurocode 4-04	Eurocode 4-04	(4.11)
$f_t = 0.46 f_{cy}^{0.5}$	From natural Tuff LWAC with a compressive strength as high as 60 MPa	(Smadi and Migdady, 1991)	(4.12)
$f_t = 0.23 f_{cu}^{0.66}$	For pelletized blast slag LWAC with cube compressive strength ranging from 10 to 65 MPa	(Neville, 2008)	(4.13)
$f_t = 0.27 f_{cu}^{0.67}$	Concrete with an artificial LWA has cube compressive strength ranging between 21 to 47 MPa	(Gesoğlu et al., 2004)	(4.14)

Where f_t splitting tensile, f_{cu} cube compressive strength, f_{cy} cylinder compressive strength.

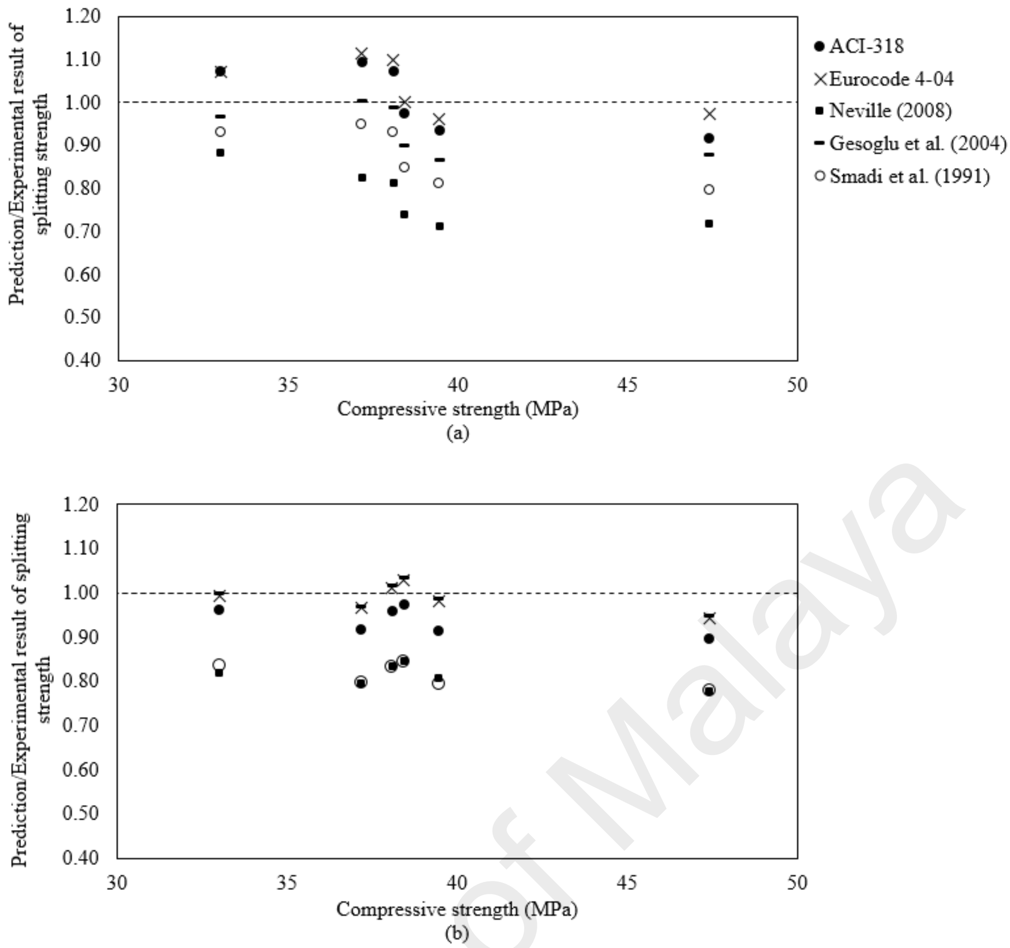


Figure 4.22: Prediction/Experimental results of 28-day splitting tensile: (a) POC concrete; (b) POCP concrete mixes

4.3.2.4 Flexural Strength

The flexural strength results of POC and POCP concretes at 28 days are shown in Figure 4.23. The results reveal that, as the POC coarse content increases, the flexural strength decreases. All POC concretes have slightly lower flexural strength values compared to that of control concrete. At 28 days, the flexural strength of POC concretes was in the range of 3.75 to 4.42 MPa. The maximum reduction was at full replacement with approximately 15% lower than the control concrete. Bashar et al. (2013) stated that due to the porous nature of POC aggregate, the flexural strength values achieved ranged between 3.5-4.6 MPa which is approximately 10% of its compressive strength. However, it is observed that a significant increase of flexural strength can be achieved when POCP was incorporated to the POC concrete mixtures. The improvement was in the range of 5-

25% higher compared to POC concrete mixes. Figure 4.24 illustrate the flexural strength development with curing age of POCP concrete mixes up to 90 days. Flexural strength of POCP concretes at different ages ranged from 4.01 to 6.15 MPa and always higher than the control mix value at a specific age. This range is comparable to the results obtained by Okafor (1988) whose study revealed that with different mix designs, the flexural strength varied in the range of 4.3 to 6.2 MPa. Previous studies (Mahmud, 2008; Mannan et al., 2002; Okafor, 1988; Teo et al., 2006) also revealed that LWC have flexural strength ranged between 2.13-4.93 MPa. As stipulated in Table 4.4, POCP concretes has a ratio in the range of 9.8-11.2 for flexural to compressive strength. This is similar to study of Gambhir (2013) who reported that concrete with more than 25 MPa compressive strength under continues moist curing, the flexural strength is generally within the range of 8 to 11% of its compressive strength. Teo et al. (2006) also showed that flexural strength varied in the range of 8 to 13% of the compressive strength. Thus, these results are in good agreement with conventional values derived for concretes made with natural aggregates.

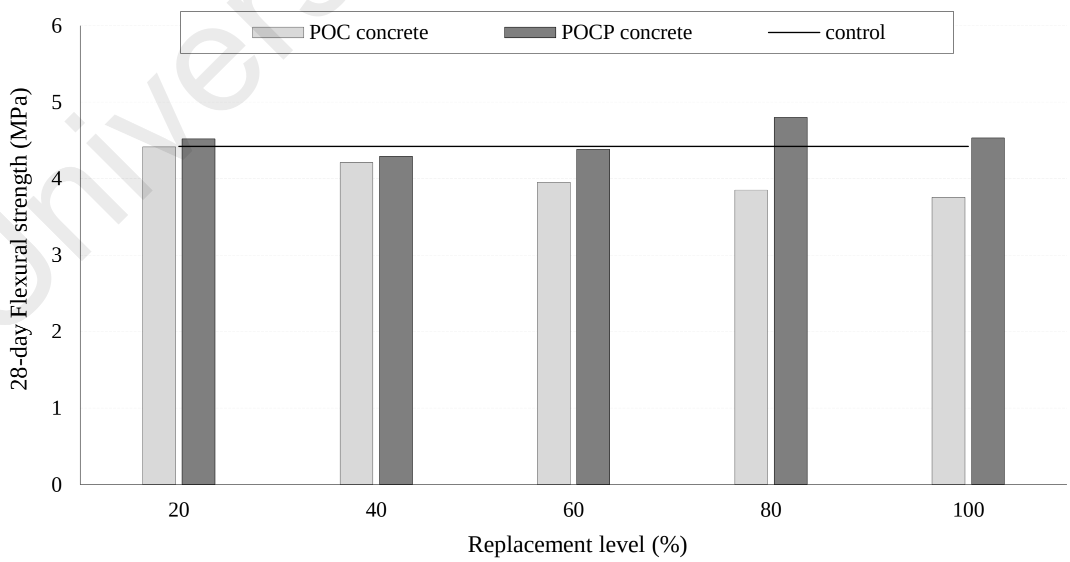


Figure 4.23: 28-day Flexural strength of POC and POCP concrete mixes

Figure 4.25 shows a comparison between the predicted values for flexural strength based on the compressive strength using several equations presented in Table 4.6. It can be observed that most of the Prediction/Experimental values of POCP concretes using different equations fall in the range of 0.8 to 1.2, indicating that the experimental measured values of flexural strength of POCP concretes in this study are comparable to the equations of (4.15), (4.16) and (4.17) were reported by Lo et al. (2004), Smadi et al. (1991) and ACI 318-8 (2008), respectively to estimate the flexural strength based on its compressive strength.

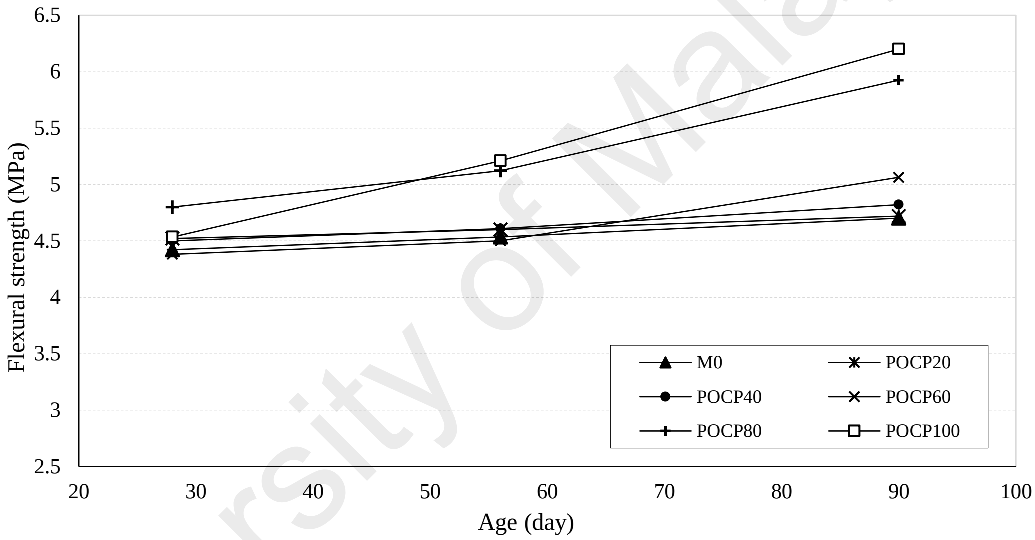


Figure 4.24: Developing of flexural strength of POCP concrete mixes

Table 4.6: Practical equations for flexural strength of concrete

Equation	Description	Reference	Equation No.
$f_r = 0.69 f_{cu}^{0.5}$	Expanded clay lightweight aggregate with cube compressive strength ranging from 29-43MP	(Lo et al., 2004)	(4.15)
$f_r = 0.58 f_{cy}^{0.5}$	From natural Tuff LWAC with a compressive strength as high as 60 MPa	(Smadi and Migdady, 1991)	(4.16)
$f_r = 0.62 f_{cy}^{0.5}$	Recommended by ACI-318	(ACI 318-08)	(4.17)

Where f_r Flexural strength, f_{cu} cube compressive strength, f_{cy} cylinder compressive strength.

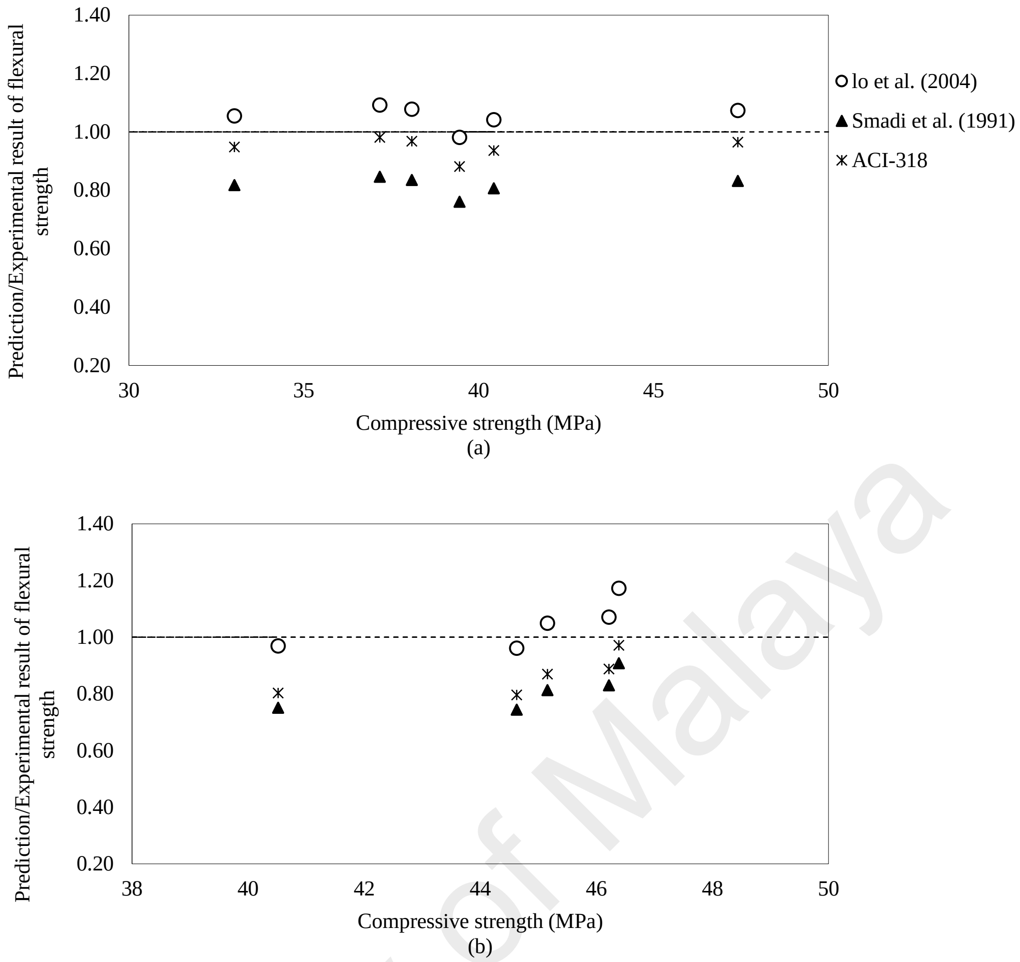


Figure 4.25: Prediction/Experimental results of 28-day flexural strength: (a) POC concrete; (b) POCP concrete mixes

4.3.2.5 Static Modulus of Elasticity

The results of modulus of elasticity (MOE) of concrete specimens containing different replacement levels of POC coarse with and without POCP are presented in Figure 4.26. POC and POCP concretes have a 28-day MOE ranging between 22 to 32 GPa and 28-day compressive strength ranged between 33 to 51 MPa. Incorporation of POC coarse negatively affect the MOE value of the concrete, POC concretes have lower MOE values than that of the control concrete with a drop of about 9 to 31%. As observed in Figure 4.26, increasing the replacement level of POC coarse for POC concretes resulted in a decrease MOE value. Series of various factors influence the resulting value of MOE mainly on the composition of the concrete ingredients i.e. cement, types of the aggregate, additives and water to cement ratio. Krizova and Hela (2014) reported that the quality of coarse aggregate greatly affects the elastic modulus of concrete. Test results of Kockal and Ozturan (2011) investigation showed that the 28-day MOE of two types of LWAC made with cold-bonded and sintered lightweight aggregates was 53% and 70% of the MOE value of normal weight concrete, respectively. A comparison between the MOE values of POC and POCP concretes at 28 days show that the addition of POCP has a significant effect on the MOE of POC concretes. POCP concretes have a 28-day MOE values range between 28-32 GPa which is 14-46% higher compared to POC concretes. The addition of POCP resulted in decreasing the water to powder ratio that benefits the elastic modulus property. Krizova et al. (2014) studied the influence of the water-binder ratio on static modulus of concrete and reported that using lower volume of mixing water reduced the number of crack created by drying and consequently improve the elastic modulus. Chi et al. (2003) demonstrated that the properties of aggregates and the water-binder ratio were two significant factors affecting the elastic modulus of concrete.

The increase of MOE values of POCP concretes with respect to POC concrete mixes can also be attributed to the enhancement of the interfacial transition zone. Domagała (2011) reported that for LWAC, a strong bond was formed between the cement matrix and aggregate due to the higher water absorption of LWA and its rough texture resulting in a higher modulus of elasticity. Furthermore, the rough surface texture further ensured that the bond between the surrounding hydrated cement paste and aggregate was better thus improving the mechanical properties of the concrete. The development of MOE values of POCP concretes up to 180 days are plotted in Figure 4.27.

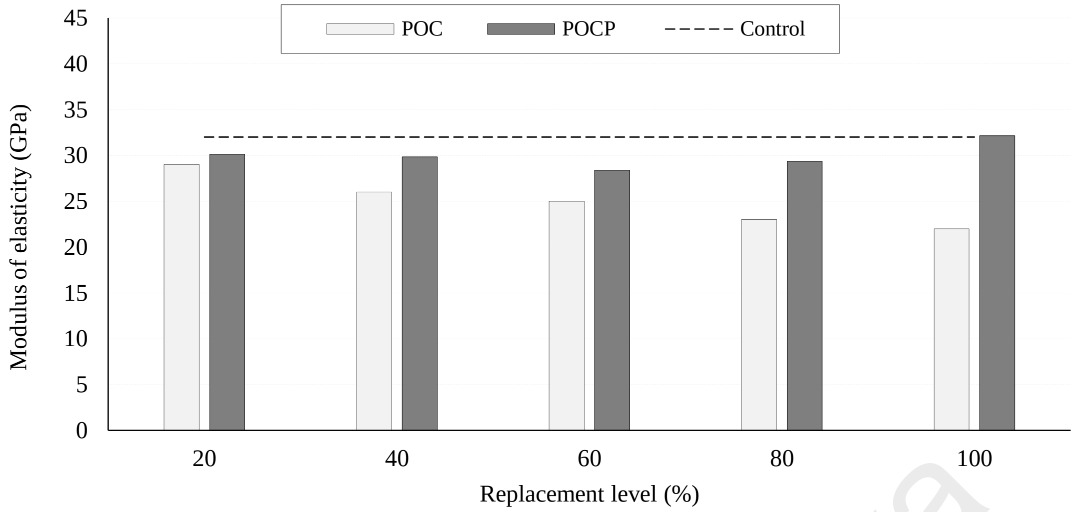


Figure 4.26: 28-day modulus of elasticity of POC and POCP concrete mixes

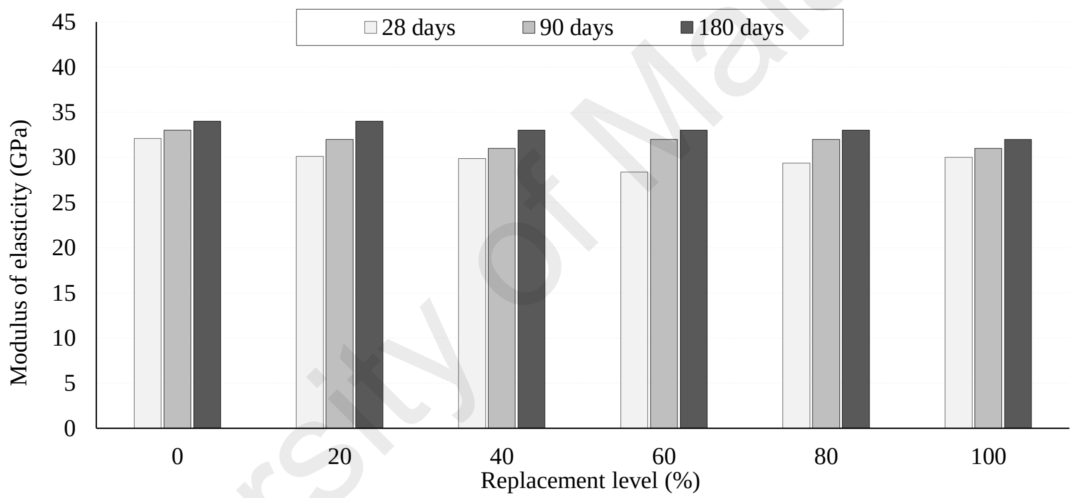


Figure 4.27: Development of modulus of elasticity of POCP concrete mixes

The modulus of elasticity could also be correlated with the compressive strength of the concrete. Various standards and previous studies related the MOE of concrete to its compressive strength and density. Figure 4.28 shows a comparison of the MOE values of POC and POCP concretes in this study with those predicted using various equations of relevant standards and previous studies presented in Table 4.7. The formulas presented in ACI 318 defines this relationship in terms of either square root of compressive strength or combination of density and square root of compressive strength in Equation (4.19) and (4.20), respectively. This is applicable for concrete with a density ranged between 1440 to 2480 kg/m^3 and strength levels of 21–35 MPa. Hossain et al. (2011) reported an Equation (4.22) based on data for LWC incorporating pumice with 28-day density ranging from 1460–2185 kg/m^3 and cylinder compressive strength of 16–35 MPa. Equation (4.23) was proposed by Tasnimi (2004) who presented information on artificial LWA concretes with cylinder compressive strength of about 15–55 MPa.

As shown in Figure 4.28, among all equations, the MOE values of POCP concretes at 28 days become closer and comparable to the values calculated using Equations of (4.18), (4.19), (4.20), (4.21), (4.24) and (4.25) were reported by BS 8110, ACI 318-11, ACI 318-08, Eurocode 4-04, Nilson and Martinez (1986) and Noguchi et al. (2009), respectively for predicting elastic modulus of concrete in terms of its compressive strength and density. While the results using Equations (4.22) and (4.23) were reported by Hossain et al. (2011) and Tasnimi (2004), respectively were in lower side and under estimated of MOE values.

Table 4.7: Practical equations for MOE of Concrete

Equation	Reference	Equation NO.
$Ec = 0.0017 W_c^2 f_{cu}^{0.33}$	(BS 8110: Part 2)	(4.18)
$Ec = 4730 f_{cy}^{0.5}$	(ACI 318-11)	(4.19)
$Ec = 0.043 W_C^{1.5} f_{cy}^{0.5}$	(ACI 318-08, 2008.)	(4.20)
$Ec = 9500 f_{cy}^{0.33}$	Eurocode 4-04	(4.21)
$Ec = 0.03 W_c^{1.5} f_{cy}^{0.5}$	(Hossain et al., 2011)	(4.22)
$Ec = 2.1684 f_{cy}^{0.535}$	(Tasnimi, 2004)	(4.23)
$Ec = (0.062 + 0.0297 f_{cy}^{0.5}) W_c^{1.5}$	(Nilson et al., 1986)	(4.24)
$Ec = 22{,}000 f_{cy}^{0.033}$	(Noguchi et al., 2009)	(4.25)

Where E_c modulus of elasticity, W_C concrete density, f_{cu} cube compressive strength, f_{cy} cylinder compressive strength.

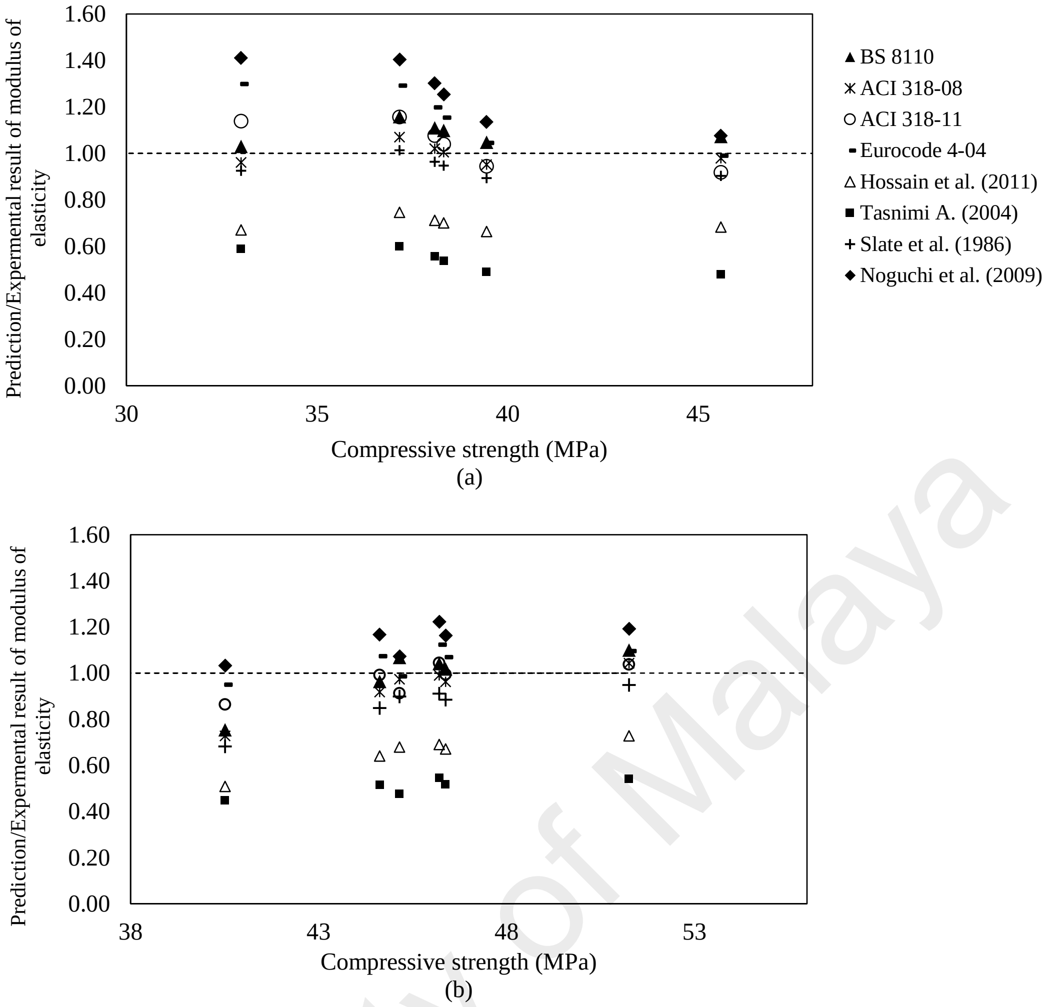


Figure 4.28: Experimental and theoretical modulus of elasticity at 28 days: (a) POC concrete; (b) POCP concrete mixes

4.3.2.6 Drying Shrinkage

The development of the shrinkage strains with drying period up to 180 days under initial water curing condition of 7 days is shown in Figure 4.29. The specimens were exposed to uncontrolled laboratory conditions with humidity ranging between 60% to 85% and temperature ranging between 26 - 35˚C. The test results have shown that POCP concrete mixes have lower drying shrinkage strain when compared to the control concrete. The addition of POCP significantly improved the drying shrinkage of POC concretes. As observed, the mixes with higher content of POCP have lower drying shrinkage. The lower drying shrinkage values of POCP concretes with respect to the control mix can be attributed to two main factors. Firstly, the incorporation of POCP reduces the pore sizes that benefit the drying shrinkage of concrete. Tangchirapat et al. (2009) reported that the transformation of large pores to fine pores decreases the evaporation of water from concrete surface and hence, reduces the drying shrinkage strain. Secondly, Dry shrinkage increases with the increase of water content of the paste (Ahmad et al., 2008). POCP concrete mixes have lower water to powder ratio compared to the control concrete, which would be expected to cause lower drying shrinkage strain. However, in general, the difference between drying shrinkage values of all the mixes are not significant at a specific age.

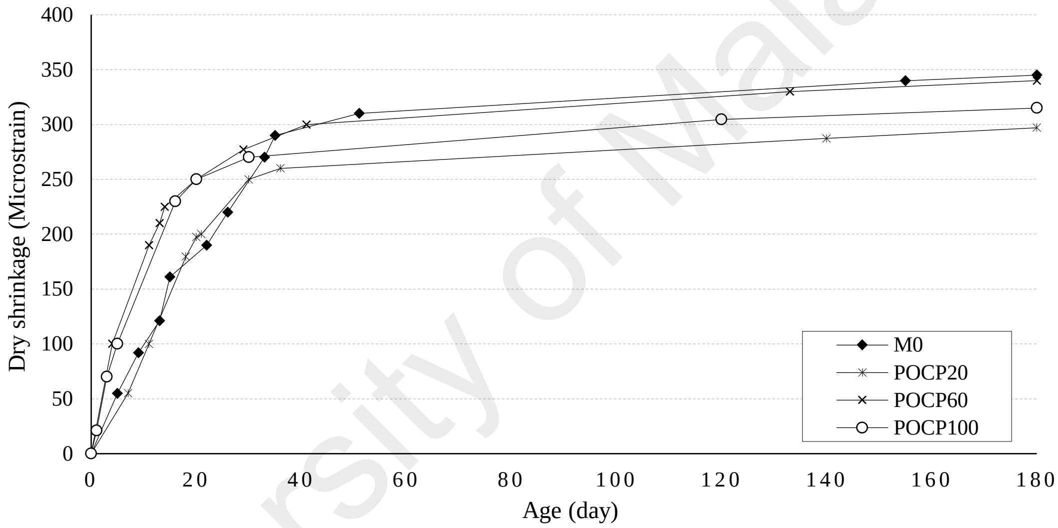


Figure 4.29: Dry shrinkage of POCP concrete mixes

4.3.2.7 Water Absorption

The measured absorption of water indicates the relative quality of near surface concrete property (Sagoe-Crentsil et al., 2001). The water absorption was carried out according to BSI 1881-122. Figure 4.30 shows the percentage of water absorption of POC and POCP concrete specimens as well as for the control mix at 28 days. It is obvious that at the same w/c ratio the water absorption of all POC concretes are higher than the control mix and tend to increase with increasing of POC coarse contents. The water absorption of POC concretes was in the range of 35 to 80% higher than that of control mix. Wongkeo et al.

(2014) stated that there is a direct relationship between the water absorption and the voids, the absorption increases as the voids increase. The lower porosity of the granite aggregate in the normal concrete mixture restricts the rate of water absorption compared to the POC concretes. Most artificial lightweight concrete exhibits significantly higher water absorption than NWC (Mannan et al., 2002) . Topcu (1997) gives the idea according to the result of his own studies that there is a parabolic connection between water absorption and concrete density, the lower concrete density the higher water absorption capacity. The results presented by Teo et al. (2010) indicated that concrete with OPS aggregates also had higher water absorption than that of conventional concrete due to the higher porosity of OPS aggregates like in other LWA concrete. Teo et al. (2010) also revealed that proper curing is essential for OPS concrete to achieve better performance at later ages. However, the values of water absorption of POCP concrete mixes are comparable to the natural aggregate concrete. The addition of POCP resulted in decrease the value of water absorption. At 28 days the reduction was in the range of 15 to 32% with respect to POC concretes. POCP benefits the concrete and resulted in more condensed microstructure. The low water absorption of POCP concrete mixes also attributed to the denser interfacial zone between the aggregate and mortar matrix with respect to that of POC concretes. Moosberg-Bustnes et al. (2004) reported that the physical effect of the mineral admixture on the concrete properties occurs as a result of pervading the fillers into the void between cement particles. Therefore, incorporation of POCP has similar effect as the mineral admixtures in the concrete by reducing the pore size which resulted in highly densified paste. Thus, decreases the water absorption. It is also obvious that SP played an important role in enhancing the fluidity of POCP concrete mixes and maximize the compaction subsequently result in high impermeable concrete. Figure 4.31 shows the percentage of water absorption of POCP concrete specimens as well as for the control concrete subjected to 7, 28, 90 and 180 days moist curing after demolding.

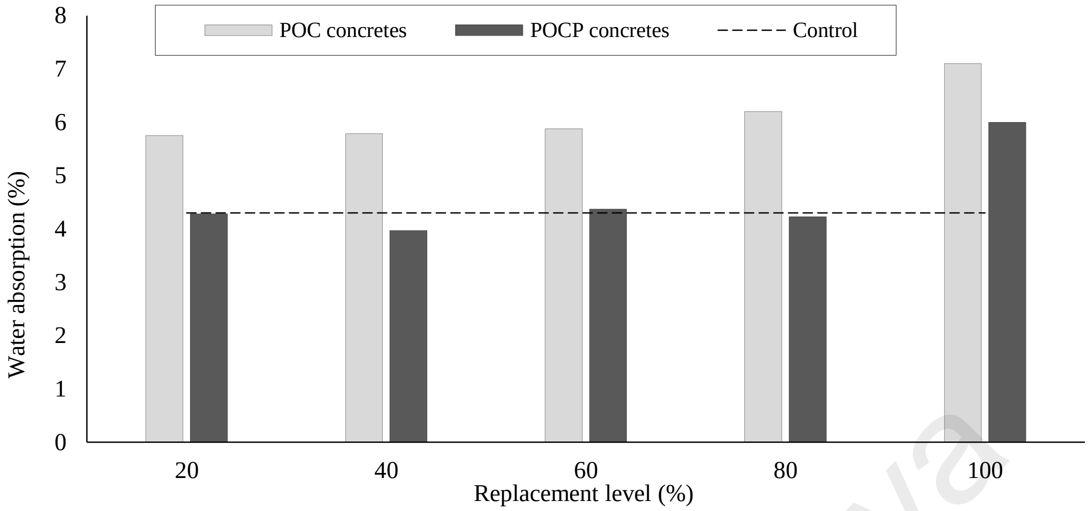


Figure 4.30: 28-day water absorption of POC and POCP concrete mixes

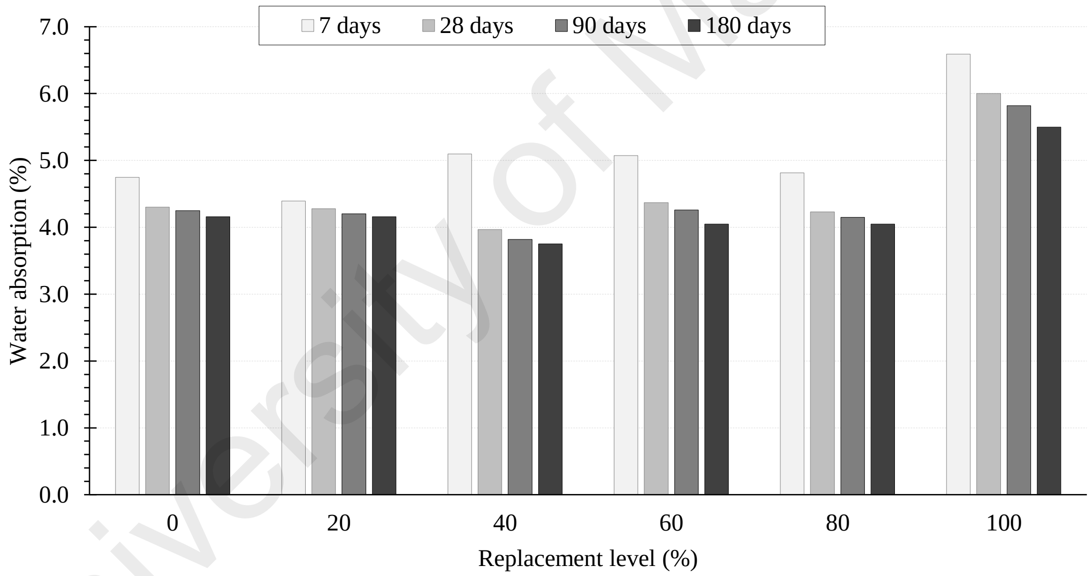


Figure 4.31: Water absorption of POCP concrete mixes at different ages

4.3.2.8 Chloride Permeability

Rapid chloride permeability test (RCPT) was conducted to investigate the performance of the concrete mixes against chloride ingress. The chloride penetration resistance of concrete is commonly used to estimate its utilization in diffusing environment, particularly rich in chloride ions, where the reinforced concrete suffers server corrosion. RCPT according to ASTM C1202 was conducted and the total charged transferring through the concrete specimens were reported. The lower the total charged passed through the concrete matrix, the higher the resistance to chloride penetration. RCPT was conducted for the mixes containing a replacement of 20, 60 and 100% of POC coarse with and without POCP as well as for the control concrete. The charged passed was obtained by measuring the average of three samples at the ages of 28, 90 and 180 days.

According to ASTM rating standard, the control concrete suffered a high chloride-ion penetrability at the ages of 28 and 90 days since the charge passed were higher than 4000 coulombs. Meanwhile, at the age of 180 days, the control concrete show moderate chloride-ion penetrability as shown in Figure 4.32. At 28 days, a slight variation in the total charge passed with respect to the percentage of POC coarse replacement was observed as shown in Figure 4.32. The chloride ion resistance of POC mixes was similar and comparable to the control concrete. The total charge passed of POC concretes was ranged between 4331 to 4895 columns felling in the range of high chloride penetrability. Similarity with a study by Chia and Zhang (2002) on LWA concrete, the results of RCPT indicated that the electric charge passed through the LWC was in the same order as those through the corresponding NWC. Furthermore, water to powder ratio ranging between 0.4 to 0.5 for conventional concretes can achieve a charge passed of 2000 to 4000 coulombs which indicated as Moderate (Shi, 2004). Meanwhile, from the results shown in Figure 4.32, a progressive reduction is observed in the chloride penetrability from POC to POCP concretes. Specimens containing POCP exhibit a greater chloride-ion resistance as compared to POC concrete mixes as well as to the control concrete. At 28 days, the charged passed of POCP concretes was in the range of 12 to 70% lower than POC concretes. The reason for the significant reduction of chloride ion penetration was due to the low water to powder ratio of POCP concrete mixes compared to POC concretes which make the concrete more densify. Chia et al. (2002) reported that the resistance of concrete to chloride penetration increases with the reduction of w/cm. At 90 and 180 days, the effect of this was even more favorable. As shown in the results presented in Figure 4.33, POCP concrete mixes exhibit a general downward trend in the amount of electrical charge passed with the age increase. Joshi and Chan (2002) stated that one of the most important factors affecting the permeability of concrete is the internal pore structure, which in turn is dependent on the extent of hydration of the cementitious materials. Therefore, more resistant to the passage of electrical current are recorded. At later ages the chloride penetration resistance of POC concrete containing POCP are classified in the category of a very low chloride permeability indicating high corrosion resistance.

It is well known that the use of supplementary cementing materials improved pore structure and reduced permeability of hardened concrete (Papadakis, 2000). Wang et al. (2008) presented data that shows the conductivity of the pore solution can be lowered with the use of mineral admixtures such as ground granulated blast furnace slag, fly ash and silica fume. Uysal et al. (2012) reported that the factor that affects the pore system of concrete is the filler effects that influence the total volume and size distribution of pores and finally affect the concrete permeability. Therefore, incorporation of POCP has similar effect as the mineral admixtures in the concrete by reducing the pore size which resulted in highly densified paste thus can lower the conductivity of the pore solution. Addition of POCP resulted in increasing powder material which benefits the permeability resistance of the ions.

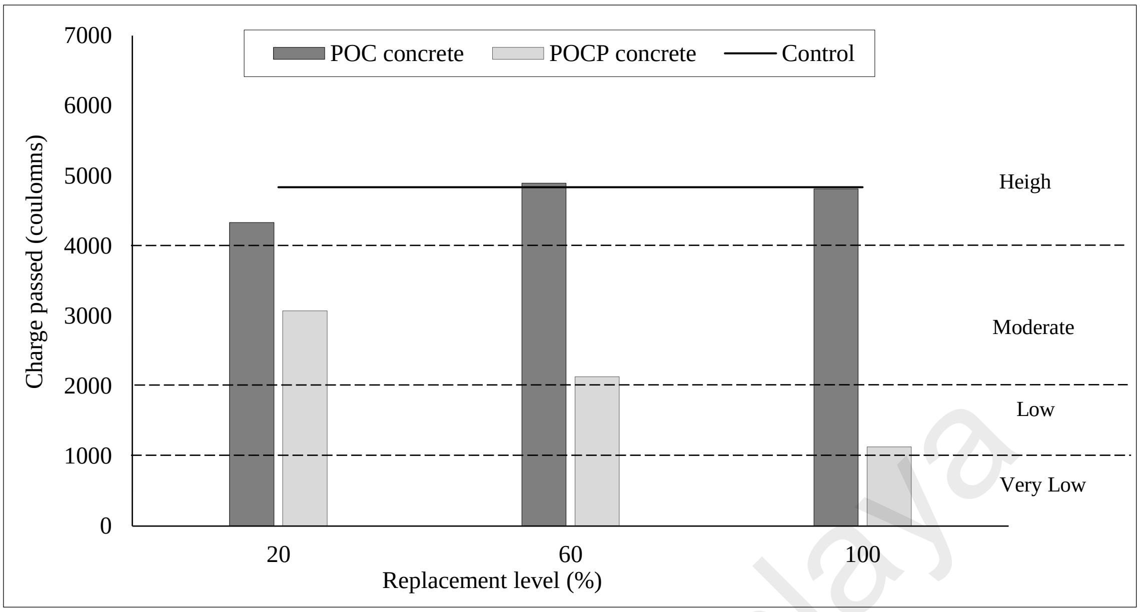


Figure 4.32: 28-day charge passed coulombs value of POC and POCP concrete

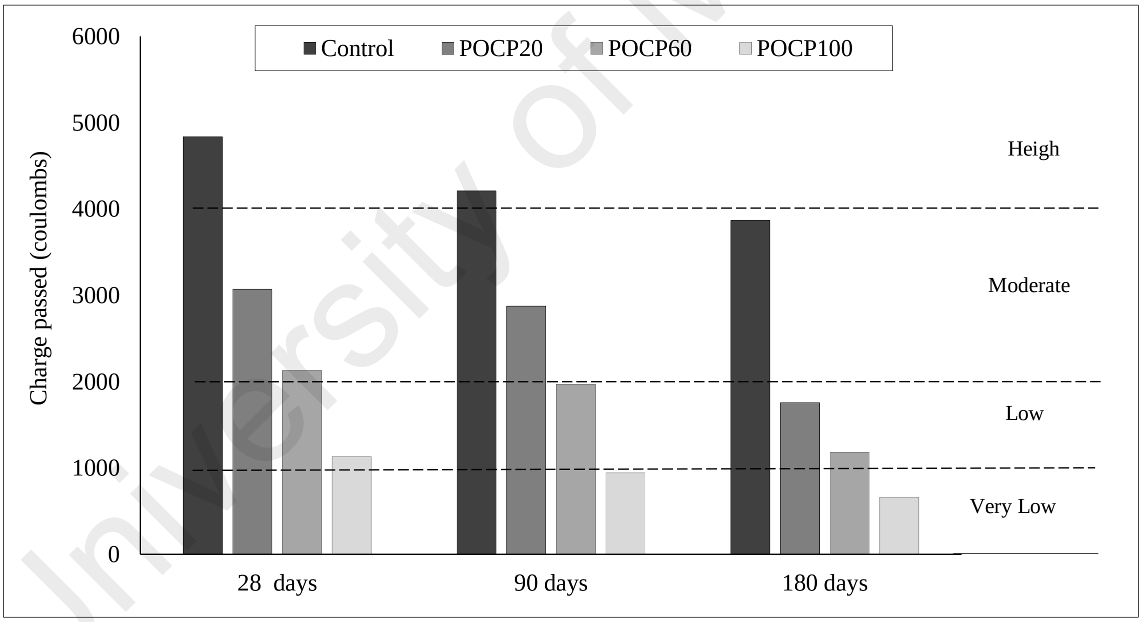


Figure 4.33: Charge passed coulombs value of POCP concrete mixes

4.4 High Strength Concrete

4.4.1 Direct Replacement

4.4.1.1 Workability

The consistency of the HSC was assessed by measuring the slump in this study. The influence of POC coarse and fine aggregates inclusion on workability are presented in Figure 4.34. The workability of the mixes was negatively affected by the replacement of POC coarse in HPOC concrete mixes, the slump was reduced by increasing the POC coarse. The higher the amount of POC, the lower the slump achieved by concrete. The mixes up to 40% replacement of POC achieved the target slump range of 150±25mm. Meanwhile, mixes with more than 40% replacement of POC coarse, the slump dropped below the minimum requirement i.e. 125mm slump. The extremely low slump recorded was for full replacement of POC coarse. This indicates that more quantities of superplasticizer required to achieve a desired workability for concrete having higher POC coarse content. Meanwhile, it can be observed from Figure 4.34 that the slump of HPOCF mixes at all the substitution levels remained within the target range of 150±25 mm slump. Therefore, the replacement of natural sand with POC fine aggregate did not affect the workability of the mixtures, and the values obtained was within the target slump range.

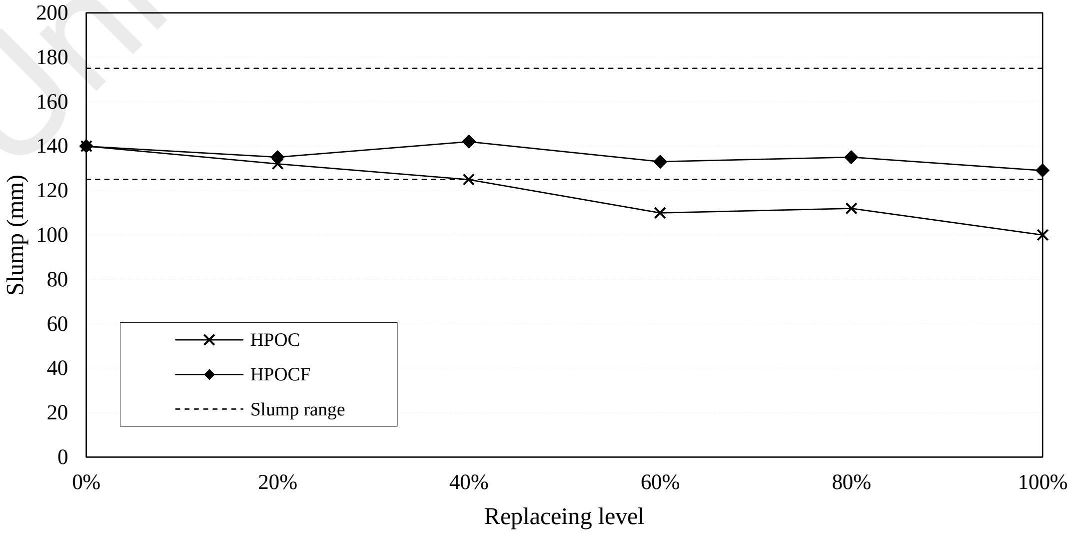


Figure 4.34: Slump values of HPOC and HPOCF concrete mixes

4.4.1.2 Fresh density

Fresh density of concrete shows a decreasing trend as the percentage of POC increases. The decreasing trend was very slight when POC was replaced with natural fine aggregate, the reduction in fresh density of HPOCF concretes are in low range between 2 to 6% lower than the control concrete. The same trend was noted for HPOC concretes. Fresh density of HPOC was in the range of 2050–2293 kg/m^3 as shown in Figure 4.35. The maximum reduction was at full replacement of POC coarse, which registered a value of 15% less than that of control mix i.e. 2389 kg/m^3.

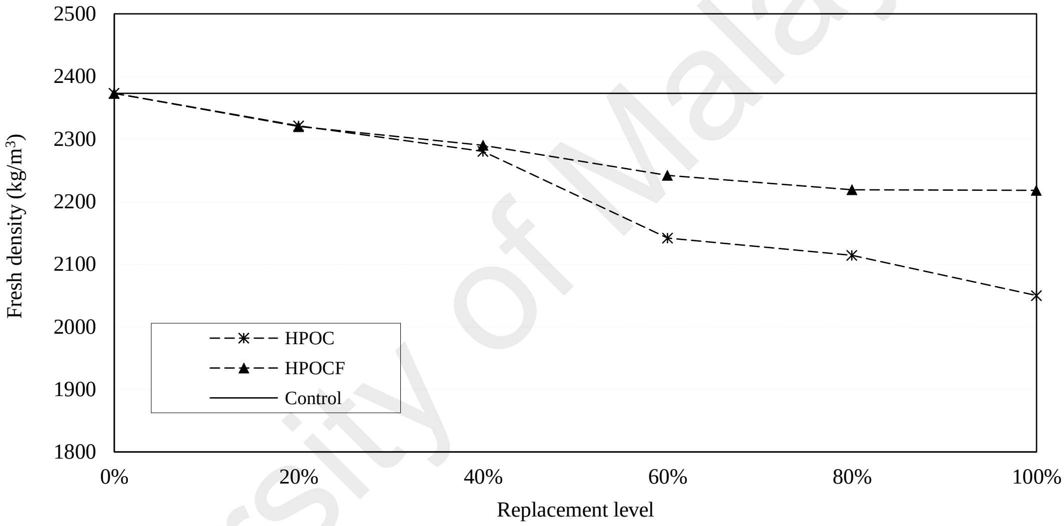


Figure 4.35: Fresh density of HPOC and HPOCF concrete mixes

4.4.1.3 Compressive Strength

The compressive strength was determined in accordance with BS EN 12390-3 (2009). The results showed that the incorporation of SF marginally increased the cement efficiency indices of the mixture. The use of SF with ultra-fine particles accelerates the rate of gain in compressive strength at the early age of concrete. The control concrete with an age of 7 days gained strength of 77% of 28-day strength. At 28 days, the compressive strength of control concrete achieved 93 MPa. However, the rate of strength development was steady or reach to an ultimate strength as the age increases. The reason behind this improvement is due to the small particles size and the fineness content of SF, which accelerates the pozzolanic reaction resulting in improved compressive strength. SF also significantly modified the microstructure of the interfacial between aggregates and the matrix. The modification of microstructure due to filling of pores with micro filler was very much effective in the concrete mixes. Cwirzen and Penttala (2005) concluded that incorporation of SF to mortar strengthens the bond between the hydrated cement matrix and aggregate in the mix, thereby enhancing the strength. Meanwhile, HSC containing POC coarse exhibits lower compressive strength at all ages compared to that of control concrete made with natural aggregates as shown in Figure 4.36. The reduction in compressive strength was due to the replacement of POC coarse as all specimens were prepared by the same mix proportion. At 28 days, the compressive strength of HPOC concrete mixes varied between 55.2 to 83.5 MPa depend on the POC contents. Figure 4.37 illustrates that among different POC coarse contents the maximum reduction of the compressive strength was at full replacement of POC, which registered a value of 40% lower than the control mix. The reduction of compressive strength observed in HPOC concrete was attributed to the porosity of POC, the strength and stiffness of POC were much lower than the normal coarse aggregate. It is clearly observed that the reduction in compressive strength in HSC is bigger as compared with the reduction in normal concrete due to the replacement of POC coarse. Meanwhile, the decreasing trend of compressive strength is marginal when natural sand was replaced with POC fine. The compressive strength of HPOCF concrete mixes developed at 28 days varied from 79.9 to 85 MPa as shown in Figure 4.38. The reduction in strength was in the range of 8 to 17% lower than the control concrete. The maximum reduction was at full replacement. The significant reduction in the void ratio as compared to POC coarse helps to maintain the strength and making it comparable with that of normal sand. Furthermore, in smaller size fractions, POC fine and the natural sand particles are similar in packing arrangement, which helps to avoid the substantial formation of voids. The reduction in fresh and hardened densities for POCF concrete are lesser as compared to POC concrete mixes in Figure 4.4 and 4.5, which indicate that there is much reduction in the voids for POCF concrete mixes

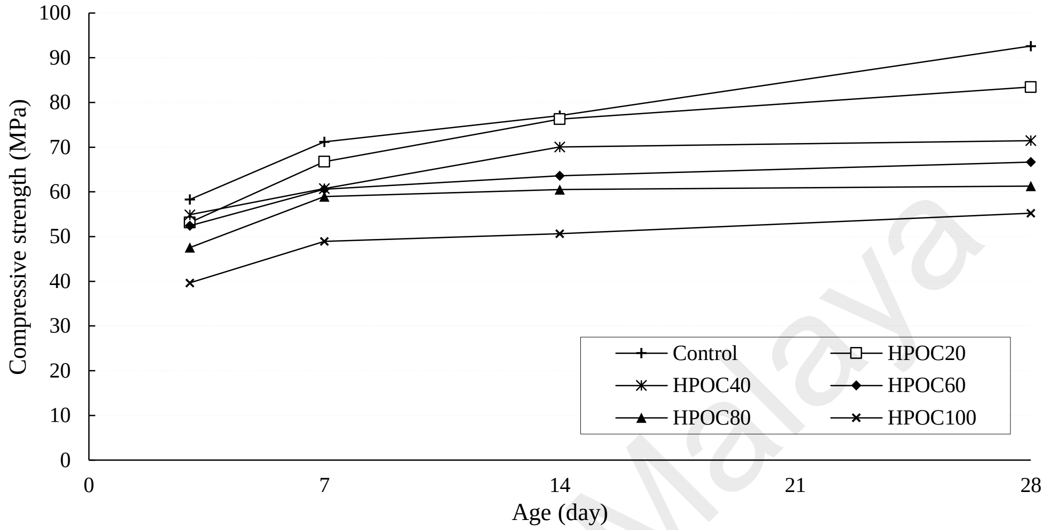


Figure 4.36: Compressive strength development of HPOC concrete mixes

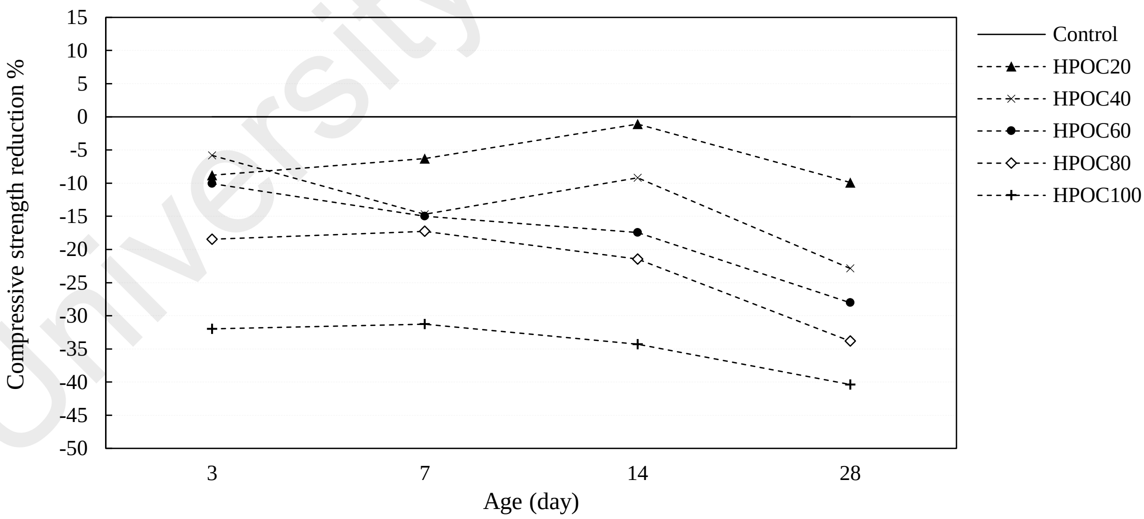


Figure 4.37: Compressive strength reduction of HPOC concretes compared to the control mix

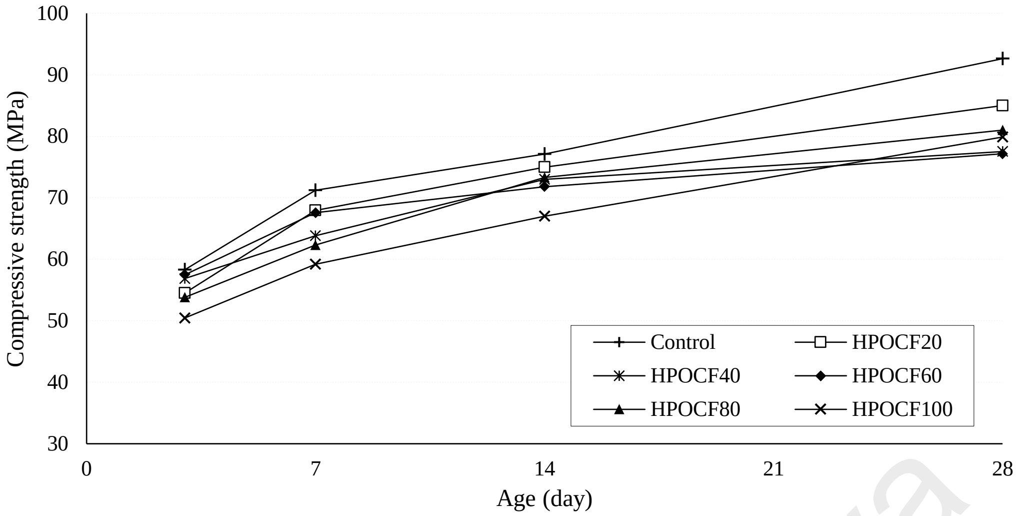


Figure 4.38: Compressive strength development of HPOCP concrete mixes

4.4.1.4 Ultrasonic Pulse Velocity (UPV)

UPV values show a decreasing trend with increase in POC contents. At 28 days, UPV reduced by between nearly 3 to 13% and 1 to 5 % for HPOC and HPOCF concrete mixes, compared to the control concrete, respectively. The reason of the reduction is attributed to the increase in air content in concrete with increase in POC. Furthermore, the result shows that there is no significant reduction in the values of UPV was observed for HPOCF concretes. The behavior of tested samples is graphically presented in Figure 4.39. Despite full replacement of POC, the specimens can achieve UPV value more than 4 km/sec, which fall in the range of a very good zone. The high UPV values can be attributed to the low w/b ratio. Ahmmad et al. (2016) reported that the hardened mortar depends on the water/cement ratio and subsequently the UPV values is affected.

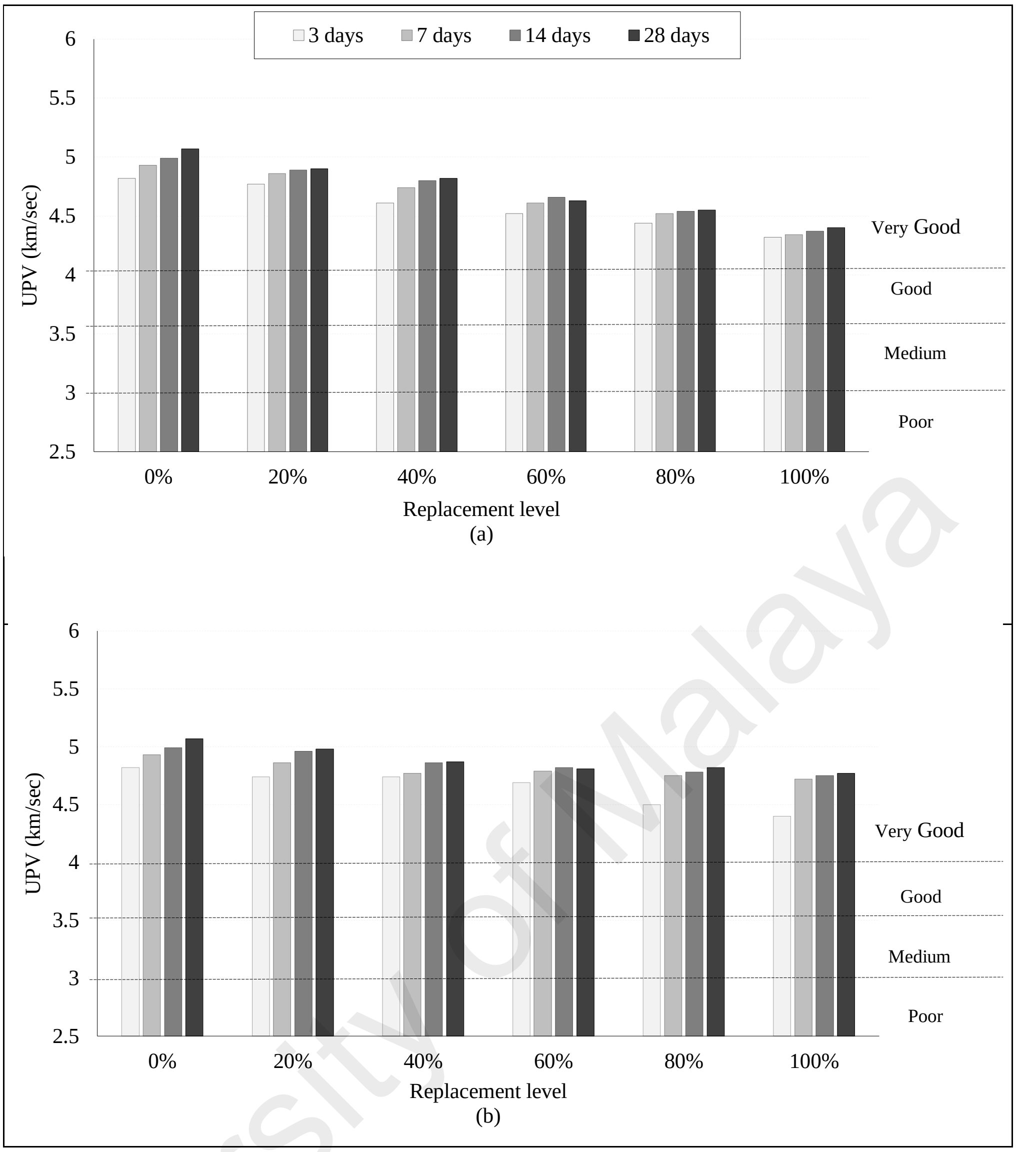


Figure 4.39: UPV values (a) HPOC (b) HPOCF concrete mixes

Figure 4.40 was plotted between compressive strength and UPV values of HPOC and HPOCF concrete mixes at ages between 3 to 28 days. The correlation coefficient of 0.83 indicates a good relationship between UPV and the compressive strength. This relationship also fitting the general Equation (4.1) which reported by (Bogas et al., 2013) and comparable to other equations reported in various studies presented in Table 4.8. Thus, this equation can be established to predict the compressive strength of HPOC and HPOCP concretes based on UPV values.

Table 4.8: Relationship between compressive strength and UPV

Relationship	R^2	Reference	Equation No.
$f_c = 1.3\ e^{0.837V_c}$	0.83	This study (HSC)	(4.26)
$f_c = 1.19\ e^{0.715V_c}$	0.59	(Nash't et al., 2005)	(4.27)
$f_c = 1.146\ e^{0.77V_c}$	0.80	(Turgut, 2004)	(4.28)
$f_c = 3.38e^{0.62V_c}$	0.61	(Bogas et al., 2013)	(4.29)
$f_c = 0.32e^{0.9895V_c}$	0.51	(Trtnik et al., 2009)	(4.30)

Where f_c is the compressive strength and V_c is UPV value of concrete

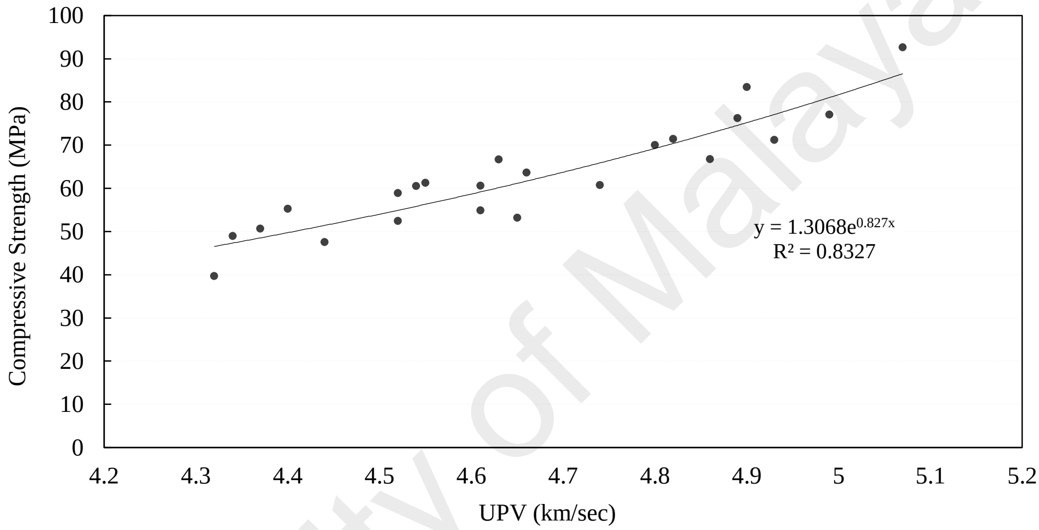


Figure 4.40: UPV-Compressive strength relationship of HPOC and HPOCF concrete mixes

4.4.2 Direct Replacement with POCP

4.4.2.1 Workability

It can be observed from Figure 4.41 that the workability of HPOCP concrete mixes are improved with the addition of POCP and the increase of SP dosage despite the low Water-binder ratio. Mixes incorporating higher content of POC coarse tend to require higher POCP content as well as higher dosages of SP to make the mixes more cohesive and to achieve the targeted slump range of 150±25 mm.

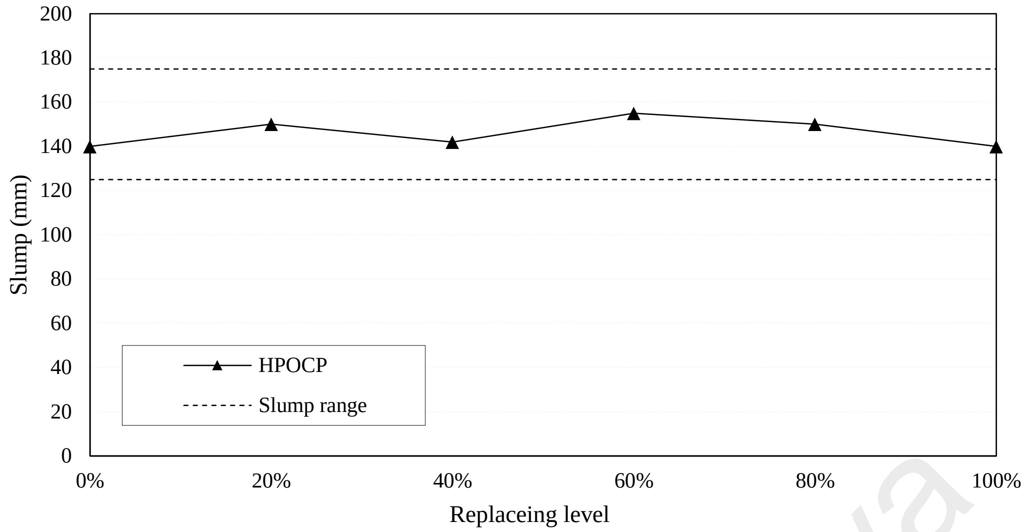


Figure 4.41: Slump values of HPOCP concrete mixes

4.4.2.2 Compressive Strength

The influence of the additional POCP on the compressive strength of HPOC concrete mixes is plotted in Figure 4.42. At 28 days, the compressive strength of HPOCP concrete mixes showed an increase between 0 to 13% with respect to the HPOC concretes. HPOCP concretes developed a compressive strength between 57 and 85 MPa depending on the POC content. The development of the compressive strength of HPOCP concretes up to 180 days are shown in Figure 4.43. All the HPOCP concrete mixes have a compressive strength lower than that of the control concrete at all ages as shown in Figure 4.44.

It well known that the aggregates has a significant role in producing HSC (Beshr et al., 2003). The use of a coarse aggregate with lower strength significantly decreases the mechanical properties of the concrete, the ultimate strength of concrete is mainly controlled by the strength of the LWA itself (Alexander and Milne, 1995; Wu et al., 2001). POC is porous and there is many more grooves and opening pores on the surface. Consequently, addition of POC coarse introduces many more voids in the mixtures leading to poor engineering properties of HSC.

Kanadasan and Razak (2015a) reported that the highly porous nature of the POC aggregate will induce crack propagation much easier than dense cement paste. As such, the aggregate failing will occur much earlier than the hardened cement paste. Additionally, the particle strength and stiffness of LWA depends on pore-size distribution, shape, and the total volume of pores in the individual particles will weaken the aggregate particles leading to weaker strength in the LWAC (Lo Cui et al., 2004) . Wilson and Malhotra (1988) reported that the compressive strength of structural LWC is directly relevant to the strength of the LWA and the hardened cement paste, as well as the bonding of the aggregate and cement paste in the interfacial zone. An inspection of the fractured surfaces showed that there is no interfacial bond failure. The failure of the specimens was mainly due to the breaking of POC. Thus, it is concluded that the weakest component in the concrete is the POC coarse rather than the ITZ between the hardened cement paste and the aggregates. The concrete strength did not benefit very much from a further improvement of the matrix strength. However, despite the reduction of the compressive strength at full replacement of POC coarse, the induced strength of 57 MPa at age of 28 days is quite satisfactory, making it suitable for many practical constructions.

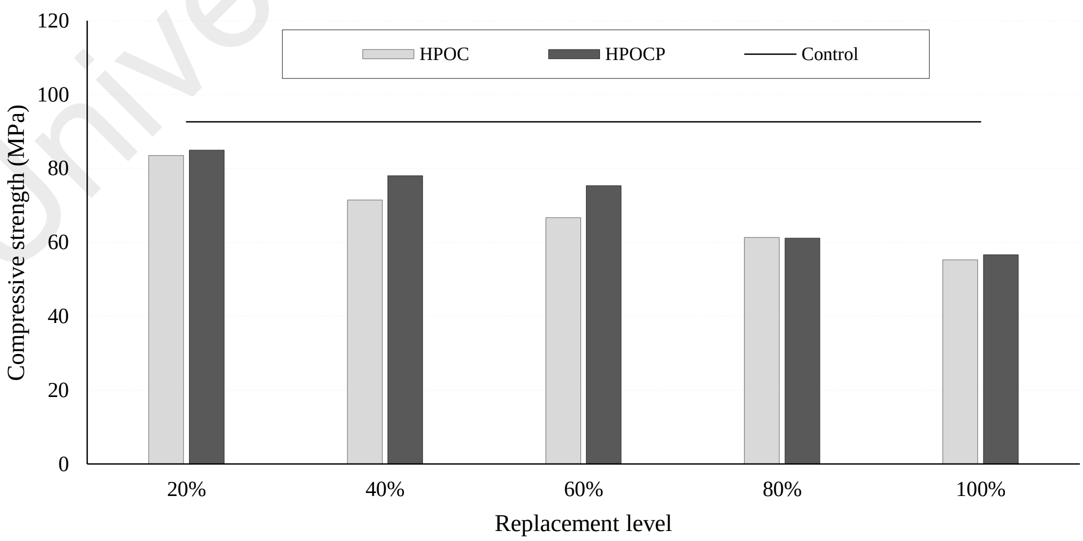


Figure 4.42: 28-day compressive strength of HPOC and HPOCP concrete mixes

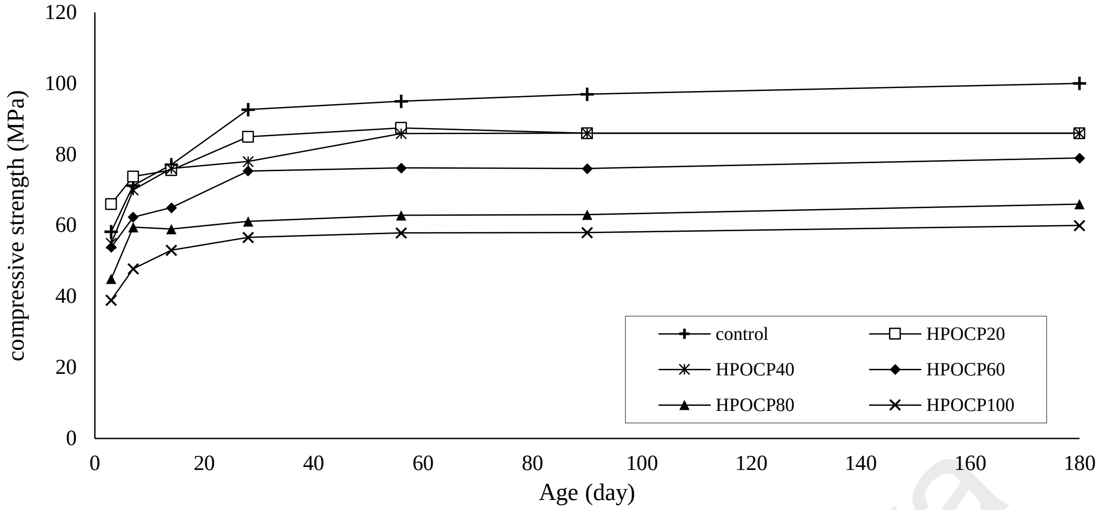


Figure 4.43: Compressive strength development of HPOCP concrete mixes

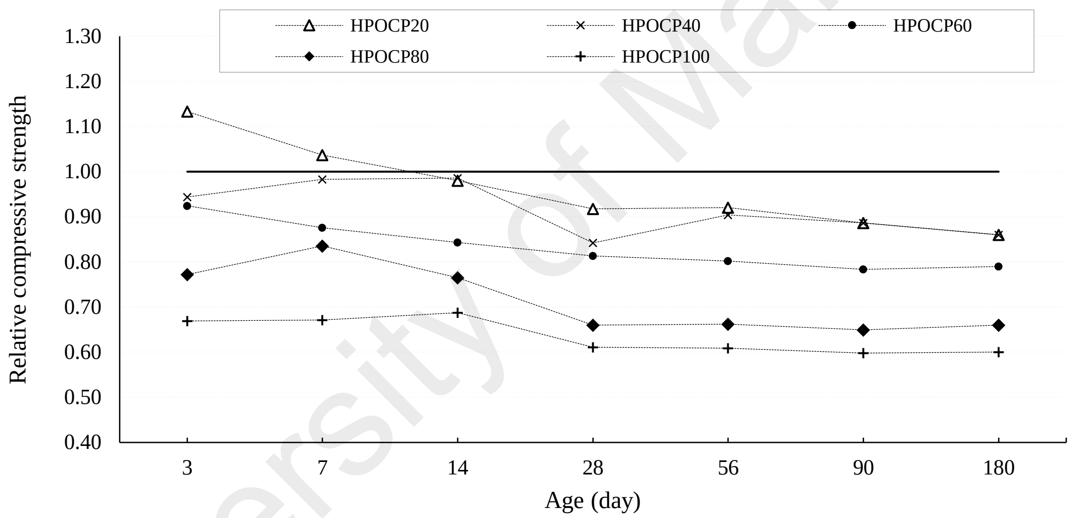
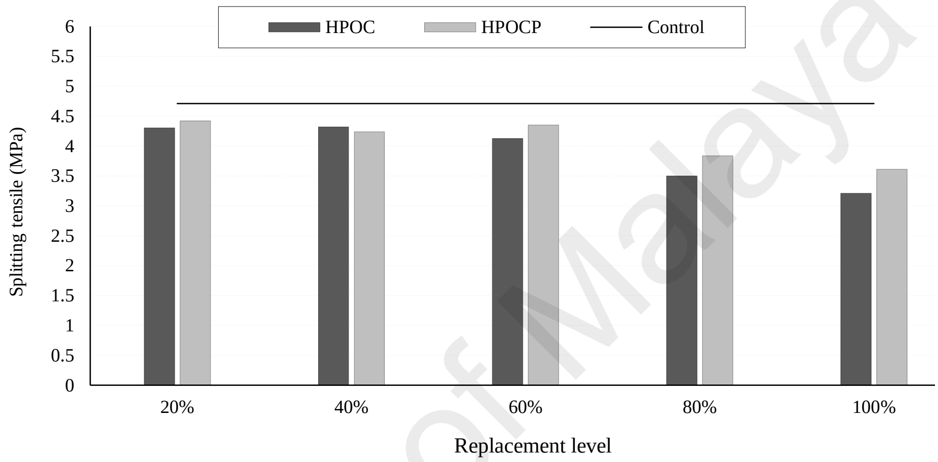


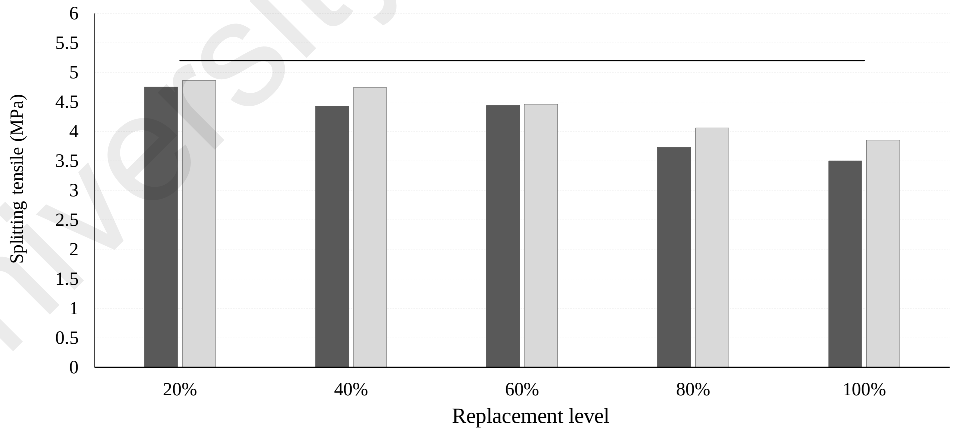
Figure 4.44: Relative compressive strength of HPOCP concrete mixes

4.4.2.3 Splitting Tensile Strength

The same trend of compressive strength is also observed for splitting tensile strength. The use of POC in HSC induces significant reduction in the splitting tensile (f_t) values. The higher the contents of POC coarse the lower f_t value as shown in Figure 4.45. At 28 days the f_t of HPOC concrete was in the range of 3.5 to 4.8 MPa. The maximum reduction was at full replacement gives a value of 32% lower than the control concrete. Meanwhile, addition of POCP offers slight improvement to the splitting tensile of HPOC mixes. At 28 days, the f_t of HPOCP increases by about 2 to 10% compared to HPOC concrete mixes as shown in Figure 4.45. As mentioned before, Aggregates have a significant influence on the properties of hardened concrete (Cho et al., 2000). The visual inspection of the broken specimens confirm that the failure of the concrete initiated within the POC coarse, which is weaker compared to matrix and aggregate-matrix interface. The development of the splitting tensile of HPOCP concrete mixes up to 90 days was measured and plotted in Figure 4.46.



(a)



(b)

Figure 4.45: Splitting tensile of HPOC and HPOCP concrete mixes: (a) 7 days; (b) 28 days

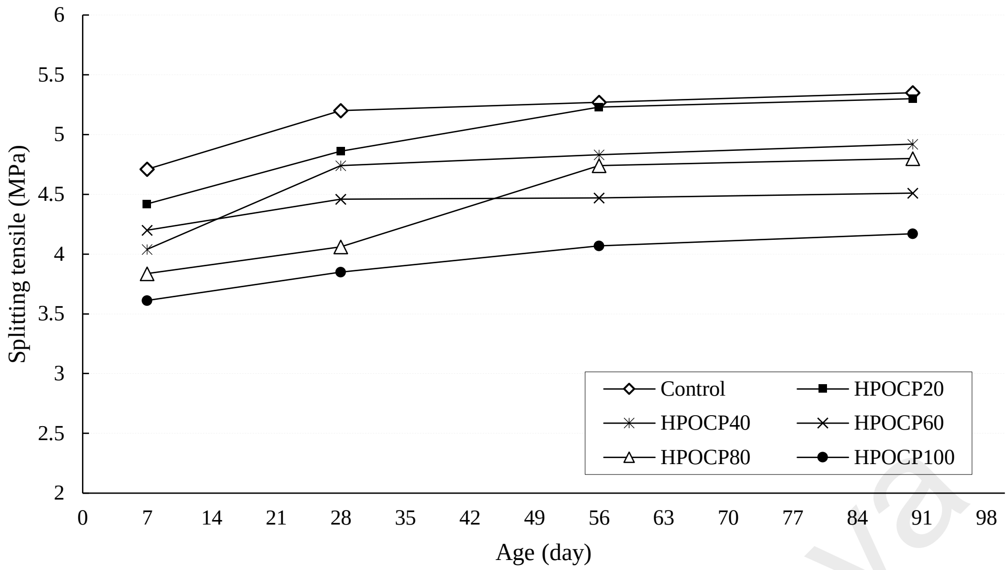
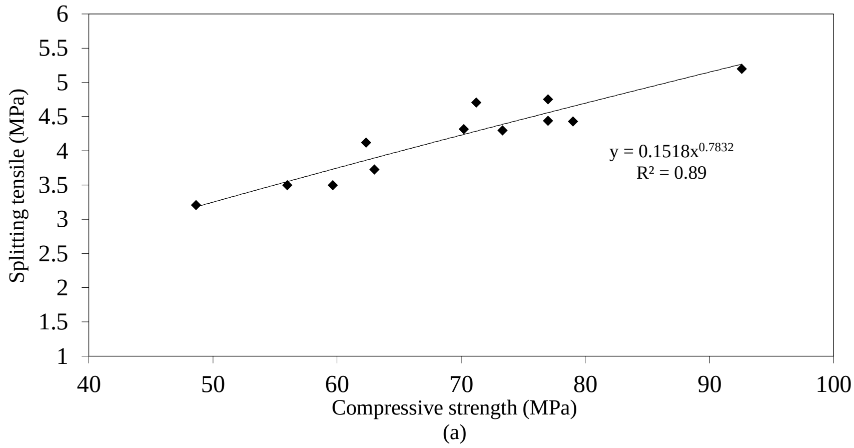


Figure 4.46: Development of splitting tensile of HPOCP concrete mixes

A parabolic relationship with correlation coefficient of 0.89 and 0.9 were observed between the 28-day compressive strength and splitting tensile of HPOC and HPOCP concrete mixes, respectively as shown in Figure 4.47. Various equations for prediction of the splitting tensile derived from the compressive strength have been proposed by previous studies and many international codes as presented in Table 4.9. Equations of (4.31) and (4.32) were proposed based on the results of this study of HPOC and HPOCP concrete mixes, respectively. Figure 4.48 shows the comparisons between the experimental results of HPOC and HPOCP concretes in this study with the results using the equations presented in Table 4.9. It can be seen that except for Equation (4.35), all the equations and the expressions provide relatively close and comparable predictions of splitting tensile strength for HPOC and HPOCP concrete mixes.



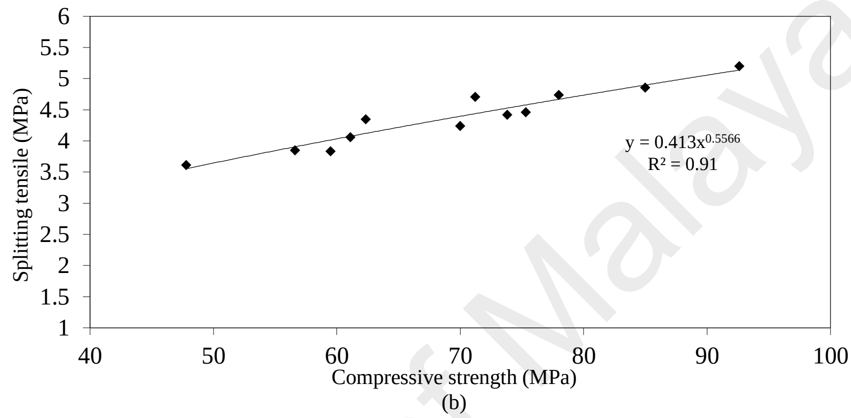
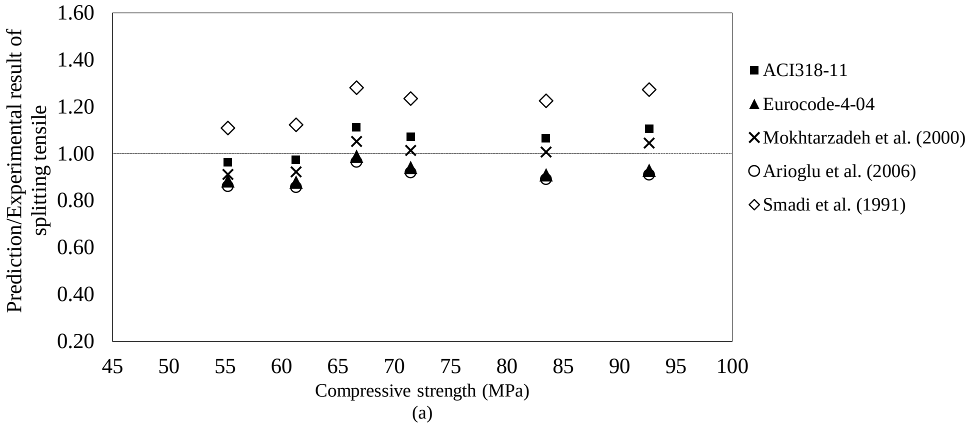


Figure 4.47: Splitting tensile and compressive strength relationship: (a) HPOC concrete; (b) HPOCP concrete mixes

Table 4.9: Practical equations for splitting tensile strength of concrete

Equation	Description	Reference	Equation NO.
$f_t = 0.152 f_{cu}^{0.78}$	HPOC concrete with cube compressive strength ranging between 45 to 92 MPa	This study (HPOC)	(4.31)
$f_t = 0.41 f_{cu}^{0.56}$	HPOCP concrete with cube compressive strength ranging between 45 to 92 MPa	This study (HPOCP)	(4.32)
$f_t = 0.53 f_{cy}^{0.5}$	ACI-318-11	ACI-318-11	(4.33)
$f_t = 0.3 f_{cy}^{0.67}$	Eurocode 4-04	Eurocode 4-04	(4.34)
$f_t = 0.46 f_{cy}^{0.5}$	From natural Tuff LWAC with a compressive strength as high as 60 MPa	(Smadi et al., 1991)	(4.35)
$f_t = 0.56 f_{cy}^{0.5}$	HSC concrete with compressive strength between 48 to 103 MPa	(Mokhtarzadeh and French, 2000)	(4.36)
$f_t = 0.32 f_{cy}^{0.66}$	Normal and HSC with compressive strength between 15 to 120 MPa	(Arıoglu et al., 2006)	(4.37)

Where f_t splitting tensile, f_{cu} cube compressive strength, f_{cy} cylinder compressive strength



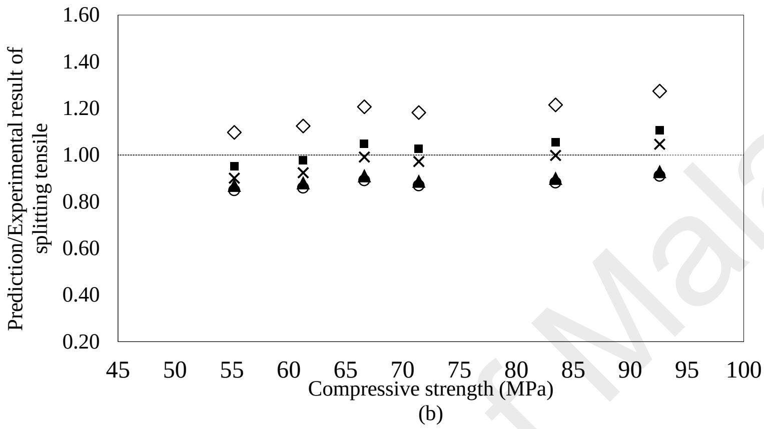


Figure 4.48: Experimental and theoretical results of 28-day splitting tensile: (a) HPOC concrete; (b) HPOCP concrete mixes

4.4.2.4 Flexural Strength

The Flexural strength of HPOC and HPOCP concrete mixes at 28 days is presented in Figure 4.49. A significant drop in flexural strength was observed up to 30% compared to the control concrete. The lower flexural strength values for concrete incorporating POC aggregate may be attributed to the higher ACV of POC, which induce premature failure when subjected to flexural load compared to control mix. The internal pores within the POC aggregate may induce early crack propagation across the specimens to allow the aggregate to fail faster compared to the cement paste (Kanadasan and Abdul Razak, 2015a). Same behavior of flexural strength has already been observed in previous research work on the utilization of waste plastic as aggregate replacement (Ismail and Al-Hashmi, 2008). However, the flexural strength of HPOCP concretes were in the range of

4 to 7.8 MPa with an improvement ranged from 1 to 9% higher compared to the HPOC concretes. Figure 4.50 illustrates the flexural strength development with curing age of HPOCP concrete mixes up to 90 days. The flexural strength of HPOCP concretes at different ages ranges from 4 to 8.5 MPa.

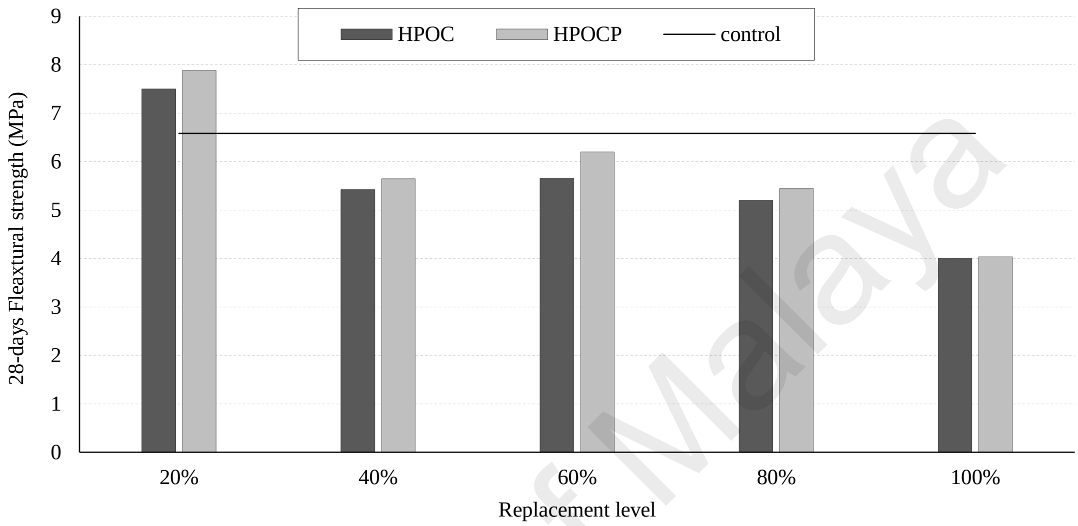


Figure 4.49: 28-day Flexural strength of HPOC and HPOCP concrete mixes

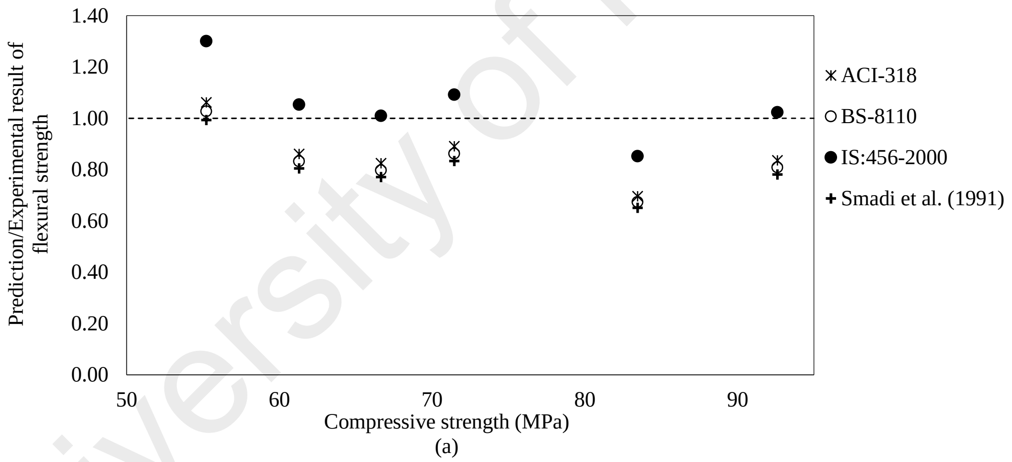
Figure 4.50: Flexural strength development of HPOCP concrete mixes

Figure 4.51 shows the comparison between the predicted values for flexural strength based on its compressive strength using several equations of various standard and previous studies presented in Table 4.10 and the experimental values obtained in this study for HPOC and HPOCP concretes. It is obvious that the experimental results of this study are close and comparable to the results using Equation (4.40) which was reported by the Indian Standard IS: 456-2000, and slightly overestimated that Equations (4.38), (4.39) and (4.41) were reported by ACI-318, BS-8110 and Smadi et al., (1991), respectively for both HPOC and HPOCP concrete mixes.

Table 4.10: Practical equations for flexural strength of concrete

Equation	Description	Reference	Equation No.
$f_r = 0.62 f_{cy}^{0.5}$	ACI-318	American	(4.38)
$f_r = 0.6 f_{cy}^{0.5}$	BS-8110 & NZS-3101	Britain & New Zealand	(4.39)
$f_r = 0.7 f_{cu}^{0.5}$	IS:456-2000	Indian	(4.40)
$f_r = 0.58 f_{cy}^{0.5}$	From natural Tuff LWAC with a compressive strength as high as 60 MPa	(Smadi et al., 1991)	(4.41)

Where f_r Flexural strength, f_{cu} cube compressive strength, f_{cy} cylinder compressive strength.



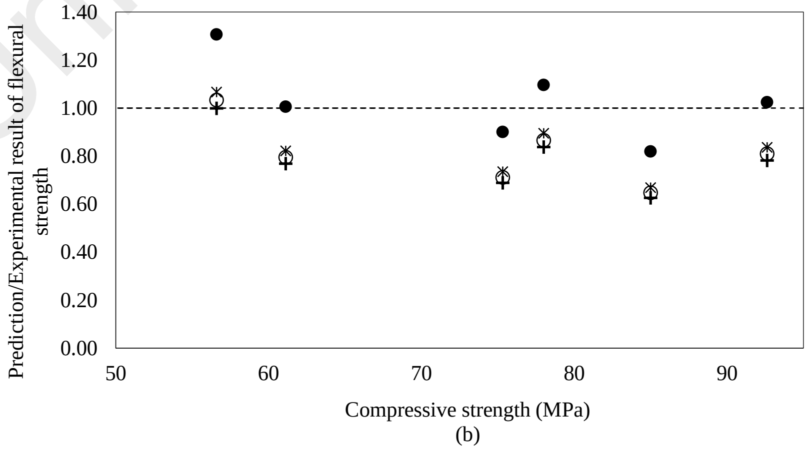


Figure 4.51: Experimental and theoretical results of 28-day flexural strength of concrete mixes: (a) HPOC; (b) HPOCP

4.4.2.5 Modulus of Elasticity

Specimen of 150 mm diameter and 300 mm high concrete cylindrical was used to assess the modulus of elasticity of the HPOC and HPOCP concrete mixes. The results of MOE at 28 days of HPOC and HPOCP concrete mixes are plotted in Figure 4.52. HPOC concretes have MOE values ranged from 30-38 GPa, which is comparatively less than that of normal weight concrete by approximately 7-26%. The MOE was affected by the stiffness and the volume of the POC used. The use of higher POC amount in the concrete mix resulted in a lower MOE values. It is well understood that MOE has a strong correlation with the compressive strength of the concrete, as well as the quality of the aggregates used in the concrete mix (Li et al., 1999). Therefore, the reduction in MOE of concretes with an increase in POC can be explained by the low elastic modulus of POC aggregates contributed by their porous structure compared to that of normal aggregates. This observation agrees with previous study of (Ozbakkaloglu et al., 2016). Generally, stiffness of LWC is less compared to NWC (Zhang et al., 2015). The MOE of the aggregate depends not only on the density, but also on the pore structure and the surface texture of the LWA (Chen et al., 1999). Baalbaki et al. (1992) reported that the elastic modulus of concrete is affected by the volume fraction and elastic properties of aggregates. Therefore, an aggregate with a dense structure and evenly distributed pores will give a higher modulus of elasticity and more concrete stiffness than a more porous aggregate. As compared to NWC, a much lower modulus of elasticity would be expected for LWC. The elastic modulus of NWC is higher because the modulus of the NWA particles are greater than that of the LWA particles (Cui et al., 2012). Meanwhile, the results show that there is slight improvement in the MOE of the HPOCP concrete mixes as a result of the additional POCP, the improvement was ranging between 3 to 10% higher compared to HPOC concrete mixes.

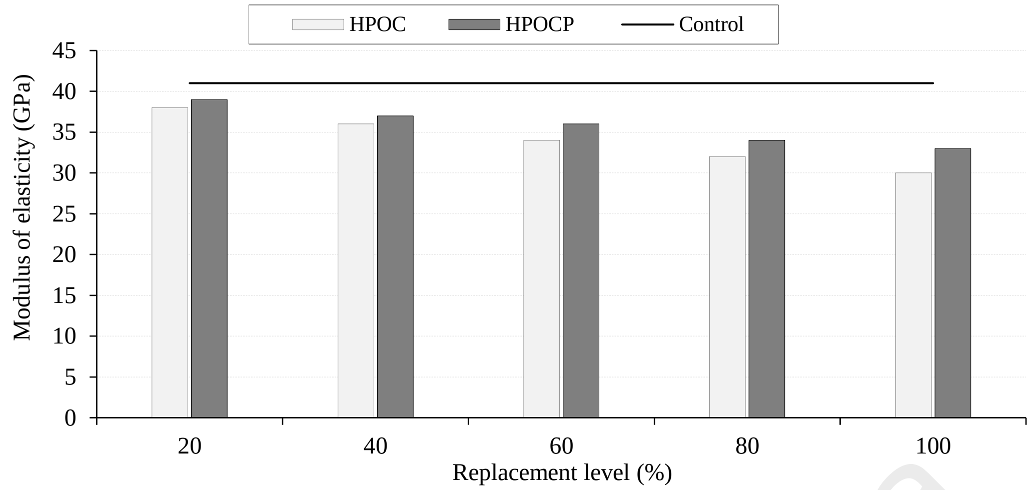


Figure 4.52: 28-day modulus of elasticity of HPOC and HPOCP concrete mixes

Figure 4.53 compares the measured MOE values obtained in this study for HPOC and HPOCP concrete mixes with those reported by the relevant standards and previous studies as presented in Table 4.11. As shown in Figure 4.53, among all equations, the MOE values calculated using Equations of (4.42), (4.43), (4.44), (4.45) and (4.49) where reported by BS 8110: Part 2, ACI 318-11, ACI 318-08, Eurocode 4-04, and Noguchi et al. (2009), respectively provide relatively close and comparable predictions MOE for HPOCP concretes. While, the results using Equations (4.46), (4.47) and (4.48) where reported by Hossain et al. (2011), Tasnimi (2004), and Nilson et al. (1986), respectively underestimated MOE than the results of HPOCP concrete mixes.

Table 4.11: Practical equations for modulus of elasticity of concrete

Equation	Reference	Equation NO.
$Ec = 0.0017 W_c^2 f_{cu}^{0.33}$	(BS 8110: Part 2)	(4.42)
$Ec = 4730 f_{cy}^{0.5}$	(ACI 318-11)	(4.43)
$Ec = 0.043 W_C^{1.5} f_{cy}^{0.5}$	(ACI 318-08, 2008.)	(4.44)
$Ec = 9500 f_{cy}^{0.33}$	Eurocode 4-04	(4.45)
$Ec = 0.03 W_c^{1.5} f_{cy}^{0.5}$	(Hossain et al., 2011)	(4.46)
$Ec = 2.1684 f_{cy}^{0.535}$	(Tasnimi, 2004)	(4.47)
$Ec = (0.062 + 0.0297 f_{cy}^{0.5}) W_c^{1.5}$	(Nilson et al., 1986)	(4.48)
$Ec = 22{,}000 f_{cy}^{0.033}$	(Noguchi et al., 2009)	(4.49)

Where Ec modulus of elasticity, W_C concrete density, f_{cu} cube compressive strength, f_{cy} cylinder compressive strength.

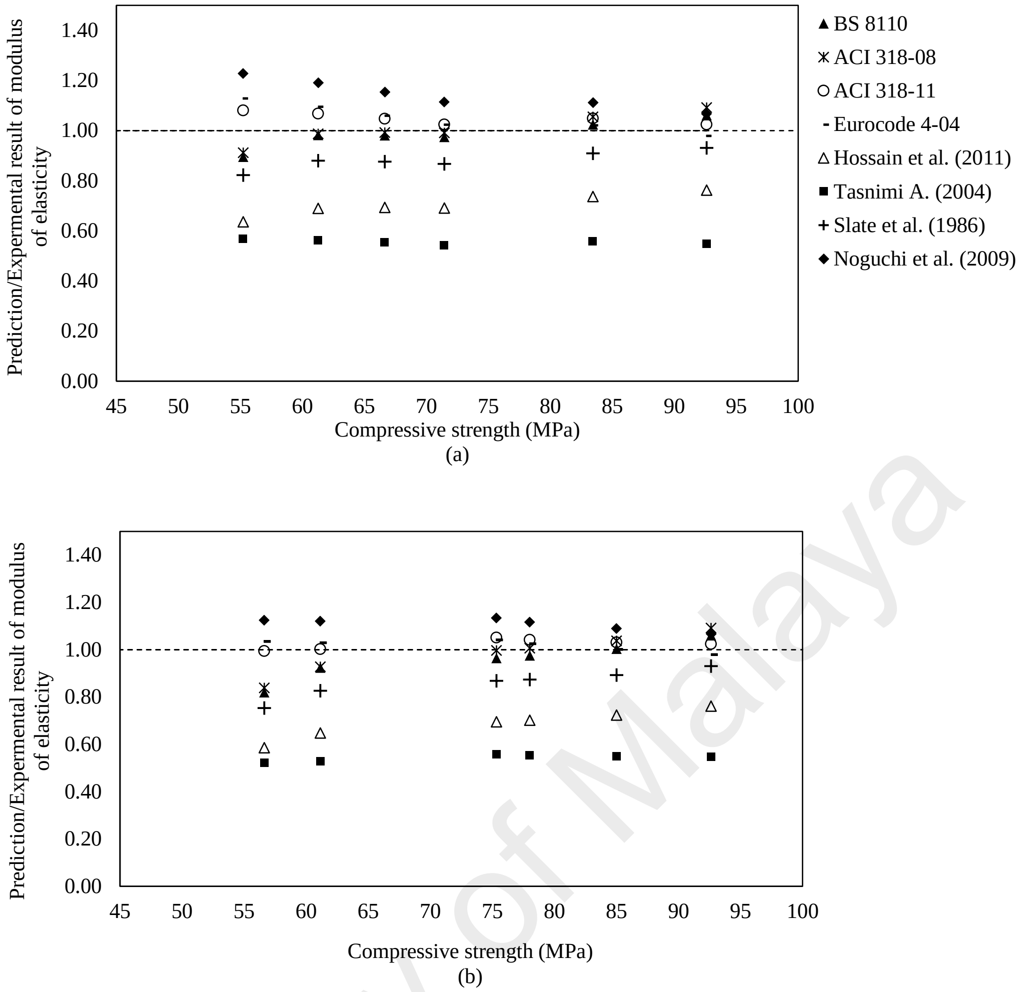


Figure 4.53: Experimental and theoretical results of 28-day modulus elasticity: (a) HPOC concrete mixes; (b) HPOCP concrete mixes

4.4.2.6 Drying Shrinkage

The drying shrinkage for HPOCP concrete specimens were measured up to 180 days after initial water curing condition of 7 days. The specimens were exposed to uncontrolled laboratory conditions with humidity ranging between 60% to 85% and temperature ranging between 26 - 35˚C. Slight variation in drying shrinkage values of HPOCP mixes was observed at different replacement levels as shown in Figure 4.54. The increasing trend of drying shrinkage was sharp at early ages up to 28 days for all the mixes. However, after 50 days a constant range of shrinkage values was observed. At later ages the mixes of HPOC20, HPOCP60 and HPOCP100 showed slightly higher shrinkage values of about 19%, 20% and 15%, respectively compared to the control mix. This observation is agree with previous study by Mannan et al. (2002) on investigation the drying shrinkage of OPS concrete and NWC up to 90 days. They reported that the drying shrinkage was increased with age, but OPS concrete showed 14% higher long-term drying shrinkage compared to NWC at the age of 90 days. However, HPOCP mixes still have comparable drying shrinkage values compared to the control concrete and the difference between all the mixes is not significant at a specific age. In general, the drying shrinkage values of all the mixes at the age of 180 days are relatively low. This is attributed to the low water-binder ration of the mixes. Ahmad et al. (2008) reported that dry shrinkage increases with the increase of water content of the paste. Furthermore, addition of POCP which resulted in decrease the w/p ration was the main parameter affecting the drying shrinkage of HPOCP concretes.

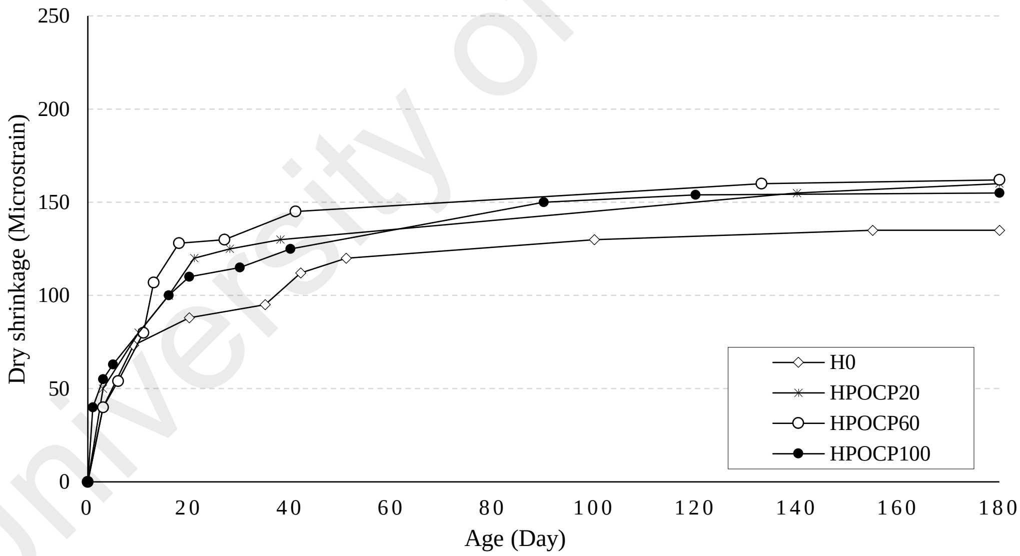


Figure 4.54: Dry shrinkage of POCP concrete mixes

4.4.2.7 Water Absorption

Water absorption capacity is a property relatively easy to study and at the same time, a factor that determines the durability index of concrete in some way. The results of water absorption test of HPOC and HPOCP concrete mixes at 28 days are plotted in Figure

4.55. In general water absorption capacity increases with an increase in the POC coarse content in the concrete. There is no significant variation in the water absorption capacity of concrete after POCP incorporation. The 28-day water absorption of HPOC and HPOCP concrete specimens varied between (1.35 to 3.15%) and (1.35 to 2.3%), respectively. The difference in water absorption values between the mixes is due to the difference in the porosity of POC and granite aggregates. POC has greater porosity than the granite used. Wongkeo et al. (2014) stated that there is a direct relationship between the water absorption and the voids, the absorption increases as the voids increase. However, the values of 28-day water absorption of the HPOCP concrete specimens did not exceed 2.5%. At 90 and 180 days, the water absorption was even more favorable as shown in Figure 4.56. The small values of water absorption are obviously attributed to the participation of micro silica in concrete. It is the micro silica that interacts with the binder and contributes to the compaction of the concrete structure due to formation of greater amounts of hydrated calcium silica phases. Moreover, the filling effect of SF significantly made the microstructure of concrete more condensed. Cordeiro et al. (2009) stated that the filling performance and microstructural reinforcement that accompanies such fineness contributes to the refinement of the pores and the total pore volume. Mazloom et al. (2004) illustrated that SF can greatly reduce the permeability of water in a lean concrete. Therefore, a better matrix of the concrete is formed. Furthermore, HSC with low w/c ratio also reduces the permeability, which is beneficial to the concrete since the external moisture ingress into concrete is substantially restricted.

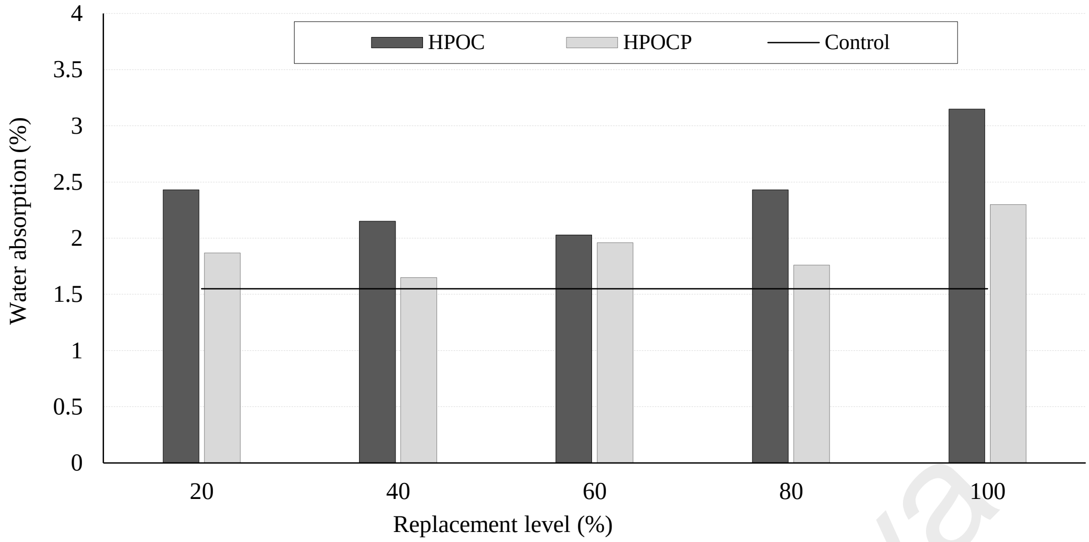


Figure 4.55: 28-day water absorption of HPOC and HPOCP concrete mixes

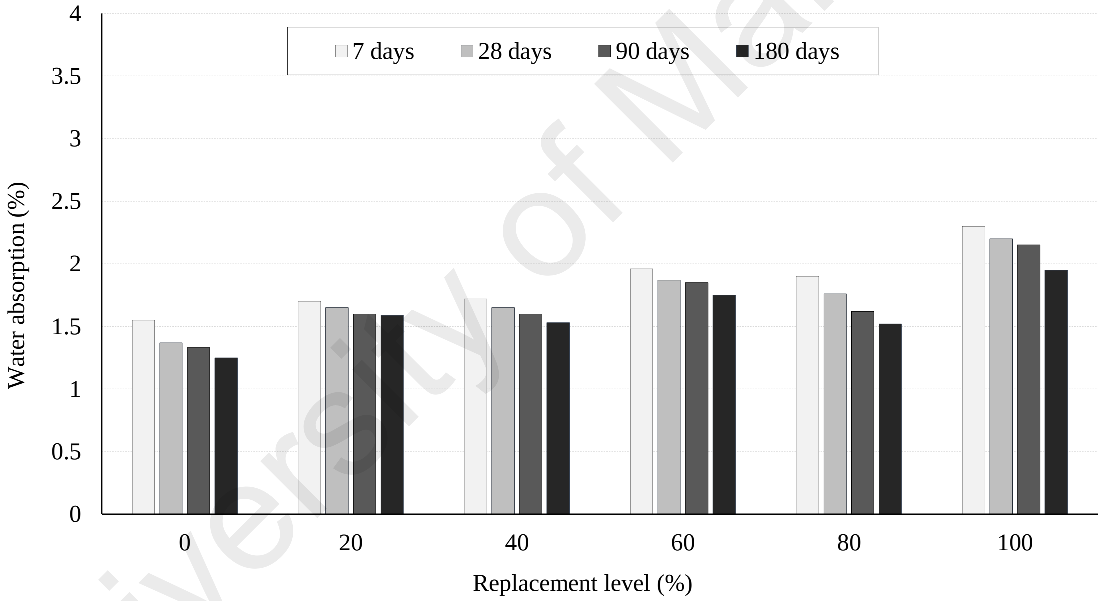


Figure 4.56: Water absorption of HPOCP concrete mixes at different ages

4.4.2.8 Chloride Permeability

The RCPT was conducted according to ASTM C1202 and the total charge transferred through the concrete specimens were reported. RCPT was conducted for the mixes has a replacement of 20, 60 and 100% of POC coarse with and without POCP as well as for the control concrete. The charge passage in coulomb was obtained by measuring the average of three samples at the ages of 28, 90 and 180 days. The results show that all HPOC and

HPOCP concrete mixes illustrated good resistances to chloride penetration. All the mixtures of HPOC and HPOCP were in the very low permeability category of less than 1000 C. At 28 days, the charge passage of the HPOC and HPOCP mixes was in the rage of 280 to 390 C. As recommended by ASTM C1202, this range referred to the concrete with very low chloride ion permeability, which was associated with high durability in term of chloride penetration resistance. As shown in Figure 4.57, the addition of POCP did not exhibit any significant difference in chloride penetrability among HPOC and HPOCP concrete mixes.

As shown in Figure 4.58, at 90 and 180 days the value of charge passage in coulomb was even more favorable with a reduction in chloride ion penetration. The value of the charge passage of HPOCP concretes ranges from 236 to 317 C. This is mainly due to the extremely fine particles of SF, which are capable of being located in a very close proximity to the aggregate particles, and the pozolanic reaction almost was completed after 90 days. Thus, the permeability of the specimens is lesser when compared to those of the early ages. Generally the passage of charge depends on the microstructure, chemical composition of binder and the pore solution in the concrete (Wee et al., 2000). Chia et al. (2002) stated that the quality of mortar matrix is the most important parameter that controls the permeability of high-strength concrete regardless of the aggregate used. Hooton et al. (2004) investigated the chloride penetration resistance of high-performance concretes. They reported that concretes containing SF and GGBF slag exhibited improved chloride penetration resistance compared to those of plain Portland cement concretes. Therefore, SF together with POCP additive were the main parameters that significantly affecting the charge passage through the concrete specimens. The filling effect of silica fume significantly made the microstructure of concrete more condensed. Moreover, the reduction of chloride ion penetration is also attributed to the low water to powder ratio that makes the concrete more densified.

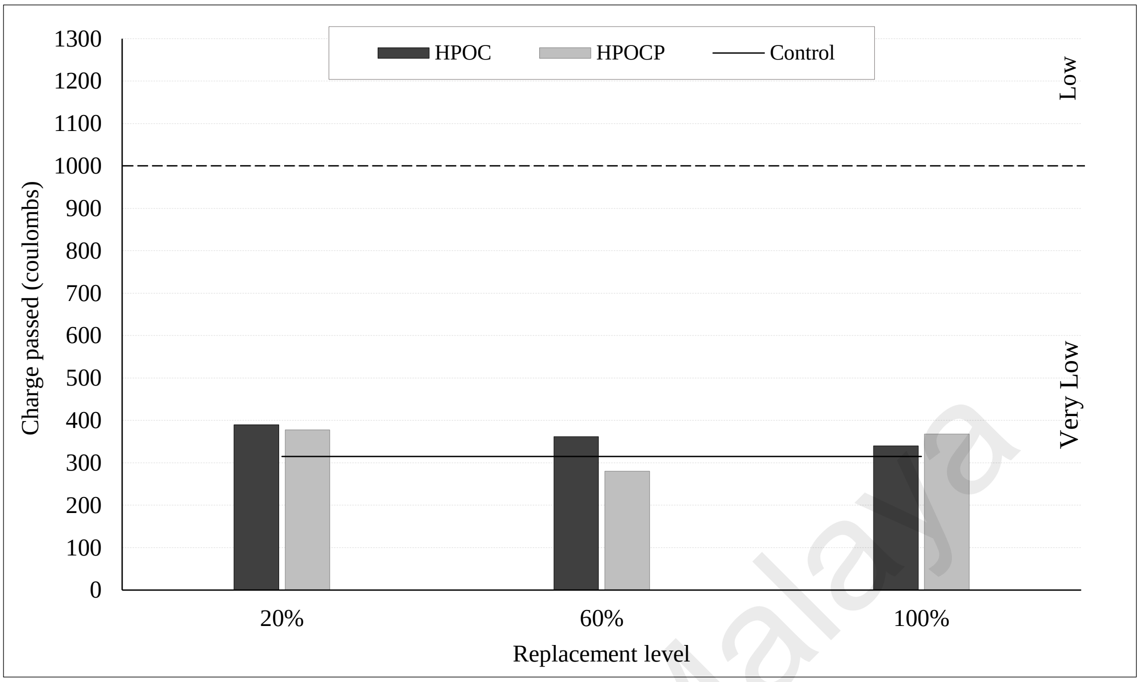


Figure 4.57: 28-day chargged passed coulombs of HPOC and HPOCP concrete

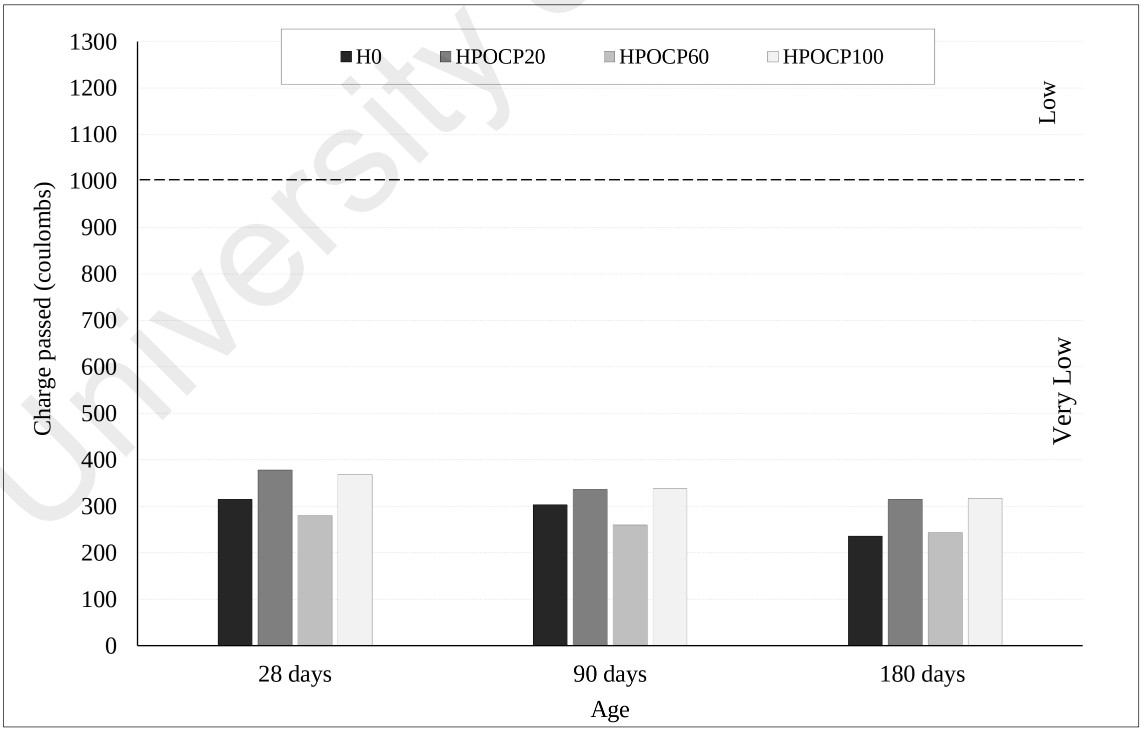


Figure 4.58: chargged passed coulombs of HPOCP concrete mixes

4.5 Cost Effective

Table 4.12 and 4.13 illustrates the approximate prices of various material used in the production of conventional and POC concrete for normal and HSC, respectively. The relationships between the cost of concrete, POC replacement ratio and engineering economic index are depicted in Figure 4.59. The total material costs of all POC mixes were lower than control concrete made with natural aggregates. The difference seems to be enlarged if replacement ratios increased. A clear reduction in cost was observed for full POC replacement compared to all the other mixes. The utilization of POC 100 significantly reduced the cost of concrete by 11% and 7 % lower than the cost of conventional concrete for normal and HSC, respectively.

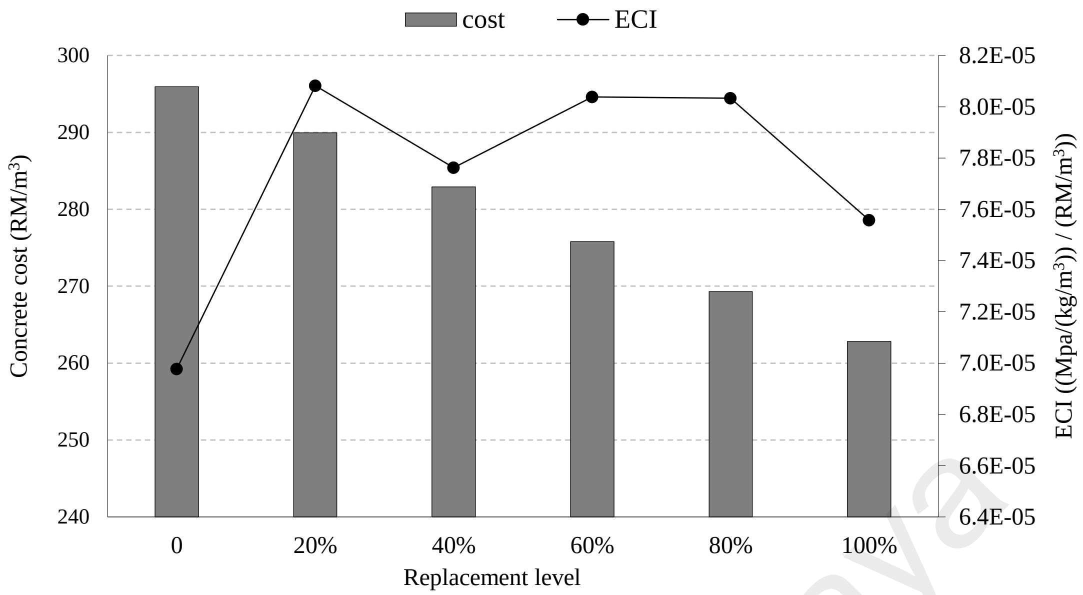
For normal POC concrete, ECI showed greater values compared to that of the control concrete mixes. POC with 20% replacement produced the highest engineering economic values compared to the other mixes. This is mainly due to the lowest cost factor involvement as POC are collected cheaply. Furthermore, the satisfactory structural efficiency also promotes good engineering economic values for the POC mixes. A decreasing trend of ECI values was observed for high strength POC concrete mixes as shown in Figure 4.59. However, intermediate replacement levels produced good engineering to cost comparison values indicating potential of POC to substitute natural aggregates. Hence, when the cost factors are compared with the hardened properties of POC which abundantly available and is obtained cheaply. The significant reduction in cost coupled with the lightweight characteristic could provide a positive contribution to the environment as well as to the economic point of view.

Table 4.12: Cost of the normal POC concrete mixes

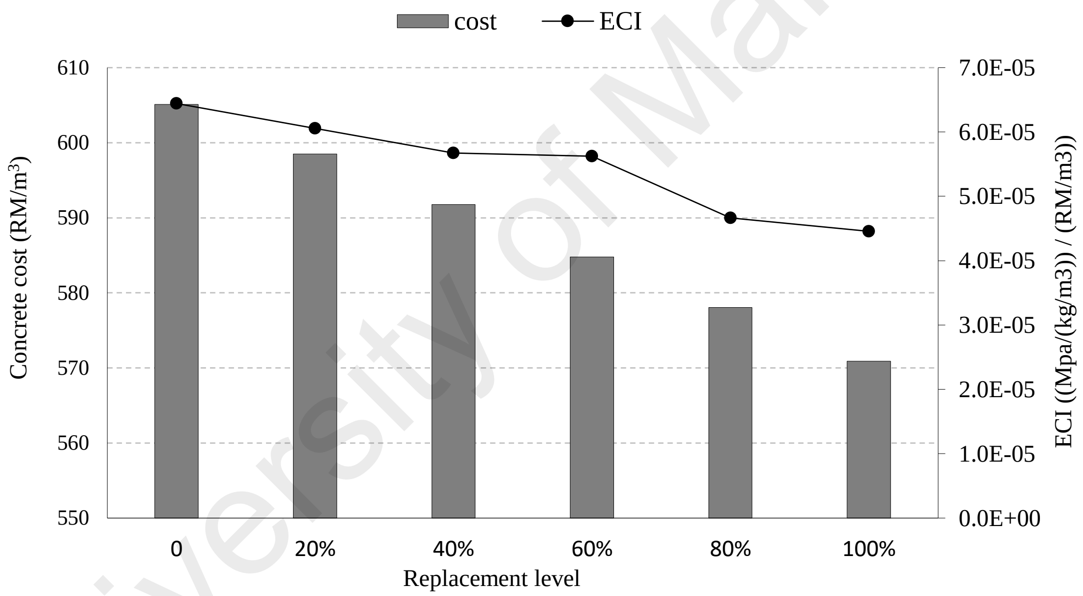
Mix proportion (kg/m^3)						
Replacement level	*Cement (OPC)*	*POCP*	*Aggregates*			**Total**
			Fine	*Coarse*		
			River Sand	*Granite*	*POC*	
Control mix	420	0	760	1007	0	2187
20%	420	70	760	806	132	2188
40%	420	93	760	604	263	2140
60%	420	108	760	403	394	2085
80%	420	156	760	201	526	2063
100%	420	203	760	0	657	2040
Material cost (RM/m^3)						**Total Cost**
Control mix	184.8	0	60.8	50.35	0	**295.95**
20%	184.8	1.4	60.8	40.3	2.64	**289.94**
40%	184.8	1.86	60.8	30.2	5.26	**282.92**
60%	184.8	2.16	60.8	20.15	7.88	**275.79**
80%	184.8	3.12	60.8	10.05	10.52	**269.29**
100%	184.8	4.06	60.8	0	13.14	**262.8**

Table 4.13: Cost of the high strength POC concrete mixes

Mix proportion (kg/m^3)							
Replacement level	*Cement (OPC)*	*POCP*	*SF*	*Aggregates*			**Total**
				Fine	*Coarse*		
				Silica Sand	*Granite*	*POC*	
Control mix	520	0	75	715	1050	0	2360
20%	520	48	75	715	840	147	2345
40%	520	88	75	715	630	295	2323
60%	520	118	75	715	420	442	2290
80%	520	158	75	715	210	589	2267
100%	520	178	75	715	0	737	2225
Material cost (RM/m^3)							**Total Cost**
Control mix	228.8	91.5	0	157.3	52.5	0	**605.1**
20%	228.8	91.5	0.96	157.3	42	2.94	**598.5**
40%	228.8	91.5	1.76	157.3	31.5	5.9	**591.76**
60%	228.8	91.5	2.36	157.3	21	8.84	**584.8**
80%	228.8	91.5	3.16	157.3	10.5	11.78	**578.04**
100%	228.8	91.5	3.56	157.3	0	14.74	**570.9**



(a)



(b)

Figure 4.59: The cost of concrete, POC replacement level and ECI relationship: (a) normal concrete mixes; (b) HSC mixes

4.6 Summary

The engineering properties and durability performance of normal and high strength concrete incorporating palm oil clinker (POC) as aggregates and filler material were evaluated. The fresh and hardened properties tests include slump, density, compressive strength, flexural strength, splitting tensile strength, modulus of elasticity, ultrasonic pulse velocity, water absorption and rapid chloride penetration. POC, being highly porous had a negative effect on the fresh and hardened concrete properties when coarse aggregate is substituted with POC. However, adopting the proposed mix design method based on the particle-packing (PP) concept was beneficial to measure the voids of POC. The PP method provided a good indication to the void present in the POC concrete mixtures. Significant improvements were noted on the mechanical and engineering properties of POC concrete after incorporating addition of POCP as void filler material. Coating POC coarse using POCP enhanced the properties of concrete making it comparable with natural aggregate concrete. It is evident that POC stands an innovative solution to produce a greener aggregate other than cost effective and environmental friendly. This finding is important for the Malaysian palm oil industry to improve the waste management and reduce environmental pollution by providing proper utilization of these abundantly available material in concrete production.

CHAPTER 5: CONCLUSIONS

5.1 General

This study is part of an extensive research program on the characteristics of concrete incorporating palm oil clinker (POC). Experimental investigation on using POC as partial and full replacement of the natural aggregates and filler material was carried in this study. Normal and high strength concrete with a target strength of 40 and 90 MPa, respectively were the design strength for the purpose of this study. The percentage of POC replacement used are 0%, 20%, 40%, 60%, 80% and 100% of the total volume of fine and coarse aggregate, separately. Particle-packing (PP) method was then adopted for the mixes where coarse aggregate was substituted with POC in order to measure the voids of POC. Addition of POCP was incorporated to the mixes as a suitable filler material to fill up the voids of POC at different replacement levels, while maintaining the other mix constituents. Fresh and hardened properties were investigated for the concrete mixes with and without POCP and compared to the control concrete which prepared using natural aggregates.

5.2 Conclusions

Based on the first objective of the study, to evaluate the effect of incorporating POC aggregate on the engineering properties of normal and high strength concrete, it was observed that POC, being highly porous, had a negative effect on the fresh and hardened concrete properties when coarse aggregate is substituted with POC. Increase of POC coarse contents led to a reduction in the mechanical properties of concrete at a given curing age. This reduction is attributed to the high amount of voids in PO C coarse. The strength and stiffness of POC were much lower than the conventional coarse aggregate due to its porosity, which significantly affects the strength carrying capacity of concrete. The maximum reduction of compressive strength was at full replacement of up to 30%

and 40% lower than the control mixes for normal and high strength concrete, respectively. Splitting tensile strength results generally showed a trend similar to that observed in the compressive strength. The maximum reduction was at full replacement of POC which registered a value of 27% and 32% lower than the control concrete for normal and HSC, respectively. All POC concrete mixes have lower flexural strength values compared to that of control concrete. The maximum reduction was at full replacement with approximately 15% and 30% lower than the control mixes for normal and HSC, respectively. The elastic modulus value of POC concrete mixes dropped by 9-31% and 7-26% lower than that of control concrete for normal and HSC, respectively. Examination of water absorption rates shown that all POC concrete mixes have higher water absorption values than the control mix and tend to increase with increase of POC contents. The chloride ion resistance of POC mixes were similar and comparable to the control concrete.

Secondly, to propose a mix design method by incorporating POC as aggregates and powder material in normal and high strength concrete production, new mix design method was developed based on the concept of Particle Packing, which was beneficial for measuring the voids of POC in the mixtures. Particle-packing method was used for each substitution levels of POC coarse. Consequently, the void volume obtained using this method was incorporated to develop the final mix proportions of normal and high strength POC concrete. POCP was then selected as the suitable filler material to fill up the voids of POC. The required amount of POCP to coat and give extra lubrication to the POC aggregate was determined for different substitution levels. Incorporating additional POCP was mainly to provide the POC aggregate with sufficient coating in order to improve the engineering properties and durability performance of concrete. The finer POCP particles have better voids-filling ability, resulting in low void space that led to improve the engineering properties of POC concrete. Additionally, utilization of POCP was also a means of maximizing the use of palm oil mill wastes in concrete production.

The third objective in this study, to determine the feasibility of using POCP as a void filler material to enhance the performance of POC concrete, the study has determined that incorporating addition of POCP significantly improve the mechanical and durability of POC concrete. POCP improved the compressive strength of POC concrete mixes by providing sufficient amount of paste to fill up the POC voids. The strength was increased by 20 - 30% and 0 to 13% higher compared to the mixes without POCP for normal and HSC, respectively. Addition of POCP improved the splitting tensile of POC concrete. The increase varied between 10to 31% and 2 to 10% higher than the mixes without POCP for normal and HSC, respectively. An increase of flexural strength can be achieved by incorporating POCP. The improvement was in the range of 5 to 25% and 1 to 9% higher compared to the mixes without POCP for normal and HSC, respectively. An improvement of elastic modulus of POC concretes was observed as a result of the additional POCP, the increase was ranging between 14-46% and 7-26% higher compared to the mixes without POCP for normal and HSC, respectively. The addition of POCP resulted in decrease the value of water absorption to be comparable to the natural aggregate concrete. A progressive reduction in the chloride penetrability was observed from POC to POCP concretes. Specimens containing addition of POCP exhibit a greater chloride-ion resistance as compared to POC mixes and the control concrete. For HSC, the results show that all HPOC and HPOCP concrete mixes illustrated good resistances to the chloride penetration. All the mixtures of HPOC and HPOCP were in the very low permeability category of less than 1000 C.

Lastly, to assess the applicability of the proposed mix design method to develop structural grade POC concrete, the study was able to determine the optimum mix proportion of POCP concrete with the best mechanical properties. Among all POCP concrete mixes, substitution of 20% of POC coarse is the optimal aggregate replacement, which gives the best strength and produced the highest engineering economic values compared to the other mixes in normal concrete production. However, it was observed that the engineering properties of normal grade POCP concrete have comparable engineering properties with the natural aggregate concrete and suitable for structural applications. Therefore, there is a great potential for the utilization of POC coarse in normal concrete production. Despite the negatively effect of POC on the mechanical properties of high strength POC concrete, the obtained results are quite satisfactory, making it suitable for many practical constructions. However, intermediate replacement levels produced good engineering to cost comparison values indicating potential of POC to substitute natural aggregates in HSC production. The significant reduction in cost coupled with the lightweight characteristic could provide a positive contribution to the environment as well as to the economic point of view. Thus, this may reduce continual exploitation of the aggregates from primary sources. Natural resources can be conserved significantly by reducing its usage and by substituting them with waste by-products. The low cost and environmentally-friendly POC aggregates provide an alternative to normal aggregates for future use.

5.3 Recommendation for Future Study

Various issues that need to be addressed by future researchers including long-term performance of POCP concrete in terms of strength properties and performance of POC concrete when subjected to aggressive environment. Studies on durability characteristics such as Alkali Silica reaction, resistance to carbonation, chemical attach and abrasion. Thermal conductivity of the material is an important field of study that will help to further clarify the ability of the material to act as a fire insulation in concrete. A comprehensive study on bonding properties of concrete incorporating POC aggregates would be another interesting aspect that can be explored.

5.4 Novelty and Contribution

This study proposed new type of local waste material namely, Palm oil clinker from the palm oil industry, can be used in the construction industry. Utilization of POC in concrete production is a suitable approach towards sustainable construction and prove proper waste management in the agricultural industry. The low cost and environmentally-friendly POC aggregates provide an alternative to natural aggregates for future use. POC aggregate concrete can help in reducing the excessive use of virgin raw materials and minimize environmental impacts concerning waste disposal and aggregate mining. The economic and environmental benefits are some of the factors that determine the viability of using POC aggregates. From an economic standpoint, using POC is cheaper compared to the costs of using natural resources or even the costs of producing new material. Thus, incorporated POC in concrete would lead to sustainable design of concrete and greener environment.

REFERENCES

Abd Elrahman, M., & Hillemeier, B. (2014). Combined effect of fine fly ash and packing density on the properties of high performance concrete: An experimental approach. *Construction and Building Materials, 58*, 225-233.

Abdullah, A. (1996). Palm oil shell aggregate for lightweight concrete. *Waste material used in concrete manufacturing*, 15, 624-636.

Abdullahi, M., Al-Mattarneh, H., Hassan, A. A., Hassan, M. H., & Mohammed, B. (2008). *Trial mix design methodology for Palm Oil Clinker (POC) concrete.* Paper presented at the Proceeding of International Conference on Construction and Building Technology (ICCBT)-(45), Malaysia.

Abeysundara, U. Y., Babel, S., & Gheewala, S. (2009). A matrix in life cycle perspective for selecting sustainable materials for buildings in Sri Lanka. *Building and Environment*, *44*(5), 997-1004.

ACI 318-08. (2008.). Building Code Requirements for Structural Concrete. *ACI Standard. Michigan (USA): American Concrete Institute;, p. 465.*

Ahmad, H., Hilton, M., Mohd, S., & Mohd Noor, N. (2007). *Mechanical properties of palm oil clinker concrete.* Paper presented at the Engineering Conference on Energy & Environment (ENCON2007), Kuching, Sarawak, Malaysia

Ahmmad, R., Jumaat, M. Z., Alengaram, U. J., Bahri, S., Rehman, M. A., & bin Hashim, H. (2016). Performance evaluation of palm oil clinker as coarse aggregate in high strength lightweight concrete. *Journal of Cleaner Production, 112*, 566-574.

Aitcin, P.-C. (1995). Developments in the application of high-performance concretes. *Construction and Building Materials, 9*(1), 13-17.

Aitcin, P. (1997). Sherbrooke mix design method. *Proceedings of the One-day Short Course on Concrete Technology/High Performance Concrete: Properties and Durability, Kuala Lumpur, Malaysia, 33pp*.

Aıtcin, P. (2003). The durability characteristics of high performance concrete: a review. *Cement and Concrete Composites, 25*(4), 409-420.

Akadiri, P. O., Olomolaiye, P. O., & Chinyio, E. A. (2013). Multi-criteria evaluation model for the selection of sustainable materials for building projects. *Automation in Construction, 30*, 113-125.

Al-Khaiat, H., & Haque, M. (1998). Effect of initial curing on early strength and physical properties of a lightweight concrete. *Cement and Concrete Research, 28*(6), 859-866.

Alengaram, U. J., Mahmud, H., Jumaat, M. Z., & Shirazi, S. (2010). Effect of aggregate size and proportion on strength properties of palm kernel shell concrete. *International journal of the physical sciences, 5*(12), 1848-1856.

Alexander, & Milne, T. (1995). Influence of cement blend and aggregate type on the stress-strain behavior and elastic modulus of concrete. *Materials Journal, 92*(3), 227-235.

Alexander, M. G. (1996). Aggregates and the deformation properties of concrete. *ACI Materials journal, 93*, 569-577.

Alnahhal, M. F., Alengaram, U. J., Jumaat, M. Z., Alqedra, M. A., Mo, K. H., & Sumesh, M. (2017). Evaluation of Industrial By-Products as Sustainable Pozzolanic Materials in Recycled Aggregate Concrete. *Sustainability, 9*(5), 767.

Alonzo, O., Barringer, W. L., Barton, S. G., Bell, L. W., Bennett, J. E., Boyle, M., . . . Carrasquillo, R. L. (1993). Guide for selecting proportions for high-strength concrete with portland cement and fly ash. *ACI Material Journal, 90*(3), 272-283.

Alshihri, M. M., Azmy, A. M., & El-Bisy, M. S. (2009). Neural networks for predicting compressive strength of structural light weight concrete. *Construction and Building Materials, 23*(6), 2214-2219.

Amparano, F. E., Xi, Y., & Roh, Y.-S. (2000). Experimental study on the effect of aggregate content on fracture behavior of concrete. *Engineering Fracture Mechanics, 67*(1), 65-84.

Arıoglu, N., Girgin, Z. C., & Arıoglu, E. (2006). Evaluation of ratio between splitting tensile strength and compressive strength for concretes up to 120 MPa and its application in strength criterion. *ACI Materials journal, 103*(1), 18-24.

Aslam, M., Shafigh, P., & Jumaat, M. Z. (2016). Oil-palm by-products as lightweight aggregate in concrete mixture: a review. *Journal of Cleaner Production, 126*, 56-73.

ASTM C330. (2007). Standard specification for Lightweight Aggregates for Structure Concrete. *Annual Book of ASTM Standards, Vol. 04.02*.

ASTM C1202, Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration, Annual Book of American Society for Testing Materials Standards, Vol. C04.02. (1993).

ASTM C1260. (2007). Standard Test Method for Potential Alkali Reactivity of Aggregates. *ASTM standards, 4*, 676-680.

ASTM C 330. (2005). Standard specification for lightweight aggregates for structural concrete. *ASTM Standards, 24*, 2269-2275.

ASTM C 618. (2001). Standard specification for coal fly ash and raw or calcined natural pozzolan for use as a mineral admixture in concrete. *ASTM Standards, 4,* 310-313.

Ayenagbo, K., Kimatu, J. N., Gondwe, J., & Rongcheng, W. (2011). The transportation and marketing implications of sand and gravel and its environmental impact in Lome-Togo. *Journal of economics and International Finance, 3*(3), 125-138.

Baalbaki, W., Aicin, P.-C., & Ballivy, G. (1992). On Predicting Modulus of Elasticity in High-Strength Concrete. *Materials Journal, 89*(5), 517-520.

Baalbaki, W., Benmokrane, B., Chaallal, O., & Aitcin, P.-C. (1991). Influence of coarse aggregate on elastic properties of high-performance concrete. *Materials Journal, 88*(5), 499-503.

Babu, K. G., & Kumar, V. S. R. (2000). Efficiency of GGBS in concrete. *Cement and Concrete Research, 30*(7), 1031-1036.

Bashar, Foo, W., & Abdullahi, M. (2014). Flexural strength of palm oil clinker concrete beams. *Materials & Design, 53*, 325-331.

Bashar, Hossain, K. M. A., Foo, W., & Abdullahi, M. (2013). Rapid chloride permeability test on lightweight concrete made with oil palm clinker. *Journal of Engineering Research and Applications,* 96,1863-1870,

Basheer, P., Gilleece, P., Long, A., & Mc Carter, W. (2002). Monitoring electrical resistance of concretes containing alternative cementitious materials to assess their resistance to chloride penetration. *Cement and Concrete Composites, 24*(5), 437-449.

Basri, H., Mannan, M., & Zain, M. (1999). Concrete using waste oil palm shells as aggregate. *Cement and Concrete Research, 29*(4), 619-622.

Behnood, A., & Ziari, H. (2008). Effects of silica fume addition and water to cement ratio on the properties of high-strength concrete after exposure to high temperatures. *Cement and Concrete Composites, 30*(2), 106-112.

Bentur, A., Igarashi, S.-i., & Kovler, K. (2001). Prevention of autogenous shrinkage in high-strength concrete by internal curing using wet lightweight aggregates. *Cement and Concrete Research, 31*(11), 1587-1591.

Beshr, H., Almusallam, A., & Maslehuddin, M. (2003). Effect of coarse aggregate quality on the mechanical properties of high strength concrete. *Construction and Building Materials, 17*(2), 97-103.

Bhanja, S., & Sengupta, B. (2005). Influence of silica fume on the tensile strength of concrete. *Cement and Concrete Research, 35*(4), 743-747.

Boddy, A. M., Hooton, R. D., & Thomas, M. D. A. (2003). The effect of the silica content of silica fume on its ability to control alkali–silica reaction. *Cement and Concrete Research, 33*(8), 1263-1268.

Bogas, J. A., Gomes, M. G., & Gomes, A. (2013). Compressive strength evaluation of structural lightweight concrete by non-destructive ultrasonic pulse velocity method. *Ultrasonics, 53*(5), 962-972.

Boukendakdji, O., Kadri, E.-H., & Kenai, S. (2012). Effects of granulated blast furnace slag and superplasticizer type on the fresh properties and compressive strength of self-compacting concrete. *Cement and Concrete Composites, 34*(4), 583-590.

Bragança, L., Mateus, R., & Koukkari, H. (2007). *Perspectives of building sustainability assessment.* Paper presented at the Proceedings of the International Conference Portugal SB07: Sustainable Construction, Materials and Practices—Challenge of the Industry for the New Millenium.

BS 1881: Part107. (1983). Testing concrete. Method for determination of density of compacted fresh concrete. British Standard Institution, London.

BS 1881: Part 122. (1983). Method for Determination of Water Absorption. British Standard Institution, London.

BS EN 12390-3. (2009). Testing hardened concrete. compressive strength of tests specimens. London, UK.

BS EN 12390-5. (2009). Testing Hardened Concrete. Flexural strength of test specimens. London, UK.

BS EN 12390-6. (2009). Testing Hardened Concrete. Tensile Splitting Strength of Test Specimens. London, UK.

BS EN 12390-7. (2009). Testing Hardened Concrete. Density of Hardened Concrete. London, UK.

BS EN 12390-13. (2013). Testing hardened concrete. Determination of secant modulus of elasticity in compression. London, UK.

BS EN 12504-4. (2004). Testing Hardebed Concrete: Determination of Ultrasonic Pulse Velocity. London, UK.

Chen, H., Yen, T., Lia, T. P., & Huang, Y. (1999). Determination of the dividing strength and its relation to the concrete strength in lightweight aggregate concrete. *Cement and Concrete Composites, 21*(1), 29-37.

Cheng-Yi, H., & Feldman, R. F. (1985). Hydration reactions in Portland cement-silica fume blends. *Cement and Concrete Research, 15*(4), 585-592.

Cheng, A., Huang, R., Wu, J.-K., & Chen, C.-H. (2005). Influence of GGBS on durability and corrosion behavior of reinforced concrete. *Materials Chemistry and Physics, 93*(2), 404-411.

Cheung, J., Jeknavorian, A., Roberts, L., & Silva, D. (2011). Impact of admixtures on the hydration kinetics of Portland cement. *Cement and Concrete Research, 41*(12), 1289-1309.

Chi, J., Huang, R., Yang, C., & Chang, J. (2003). Effect of aggregate properties on the strength and stiffness of lightweight concrete. *Cement and Concrete Composites, 25*(2), 197-205.

Chia, K. S., & Zhang, M.-H. (2002). Water permeability and chloride penetrability of high-strength lightweight aggregate concrete. *Cement and Concrete Research, 32*(4), 639-645.

Chindaprasirt, P., Homwuttiwong, S., & Jaturapitakkul, C. (2007). Strength and water permeability of concrete containing palm oil fuel ash and rice husk–bark ash. *Construction and Building Materials, 21*(7), 1492-1499.

Cho, S.-W., Yang, C.-C., & Huang, R. (2000). Effect of aggregate volume fraction on the elastic moduli and void ratio of cement-based materials. *Journal of Material Science and Technology, 8*(1), 1-7.

Cordeiro, G., Toledo Filho, R., & Fairbairn, E. (2009). Effect of calcination temperature on the pozzolanic activity of sugar cane bagasse ash. *Construction and Building Materials, 23*(10), 3301-3303.

Cui, H., Lo, T. Y., Memon, S. A., & Xu, W. (2012). Effect of lightweight aggregates on the mechanical properties and brittleness of lightweight aggregate concrete. *Construction and Building Materials, 35*, 149-158.

Cwirzen, A., & Penttala, V. (2005). Aggregate–cement paste transition zone properties affecting the salt–frost damage of high-performance concretes. *Cement and Concrete Research, 35*(4), 671-679.

Dahunsi, B. I. (2004). Properties of periwinkle-granite concrete. *Journal of Civil Engineering, 8*(1), 27-36.

De Gutiérrez, R., Diaz, L., & Delvasto, S. (2005). Effect of pozzolans on the performance of fiber-reinforced mortars. *Cement and Concrete Composites, 27*(5), 593-598.

Domagała, L. (2011). Modification of properties of structural lightweight concrete with steel fibres. *Journal of Civil Engineering and Management, 17*(1), 36-44.

Estrela, C., Bammann, L. L., Estrela, C., Silva, R. S., & Pécora, J. D. (2000). Antimicrobial and chemical study of MTA, Portland cement, calcium hydroxide paste, Sealapex and Dycal. *Braz Dent J, 11*(1), 3-9.

Felekoğlu, B., Tosun, K., Baradan, B., Altun, A., & Uyulgan, B. (2006). The effect of fly ash and limestone fillers on the viscosity and compressive strength of self-compacting repair mortars. *Cement and Concrete Research, 36*(9), 1719-1726.

Ferraris, C. F., Obla, K. H., & Hill, R. (2001). The influence of mineral admixtures on the rheology of cement paste and concrete. *Cement and Concrete Research, 31*(2), 245-255.

Forster, S. W. (1994). High-performance concrete: stretching the paradigm. *Concrete International, 16*(10), 33-34.

Gambhir, M. L. (2013). *Concrete technology: theory and practice*: Tata McGraw-Hill Education.

Gesoglu, M., Güneyisi, E., Nahhab, A. H., & Yazıcı, H. (2016). The effect of aggregates with high gypsum content on the performance of ultra-high strength concretes and Portland cement mortars. *Construction and Building Materials, 110,* 346-354.

Gesoğlu, M., Özturan, T., & Güneyisi, E. (2004). Shrinkage cracking of lightweight concrete made with cold-bonded fly ash aggregates. *Cement and Concrete Research, 34*(7), 1121-1130.

Girish, S., Ranganath, R. V., & Vengala, J. (2010). Influence of powder and paste on flow properties of SCC. *Construction and Building Materials, 24*(12), 2481-2488.

Golias, M., Castro, J., & Weiss, J. (2012). The influence of the initial moisture content of lightweight aggregate on internal curing. *Construction and Building Materials, 35*, 52-62.

González, M. J., & Navarro, J. G. (2006). Assessment of the decrease of CO_2 emissions in the construction field through the selection of materials: practical case study of three houses of low environmental impact. *Building and Environment, 41*(7), 902-909.

Grabiec, A. M., Zawal, D., & Szulc, J. (2015). Influence of type and maximum aggregate size on some properties of high-strength concrete made of pozzolana cement in respect of binder and carbon dioxide intensity indexes. *Construction and Building Materials, 98*, 17-24.

Haach, V. G., Juliani, L. M., & Da Roz, M. R. (2015). Ultrasonic evaluation of mechanical properties of concretes produced with high early strength cement. *Construction and Building Materials, 96,* 1-10.

Halicka, A., Ogrodnik, P., & Zegardlo, B. (2013). Using ceramic sanitary ware waste as concrete aggregate. *Construction and Building Materials, 48*, 295-305.

Halimah, M., Tan, Y. A., Nik Sasha, K. K., Zuriati, Z., Rawaida, A. I., & Choo, Y. M. (2013). Determination of life cycle inventory and greenhouse gas emissions for a selected oil palm nursery in Malaysia: A case study. *Journal of Oil Palm Research, 25*, 343-347.

Haque, M., Al-Khaiat, H., & Kayali, O. (2004). Strength and durability of lightweight concrete. *Cement and Concrete Composites, 26*(4), 307-314.

Hassan, K., Cabrera, J., & Maliehe, R. (2000). The effect of mineral admixtures on the properties of high-performance concrete. *Cement and Concrete Composites, 22*(4), 267-271.

Hobbs, B., & Kebir, M. T. (2007). Non-destructive testing techniques for the forensic engineering investigation of reinforced concrete buildings. *Forensic science international, 167*(2), 167-172.

Hooton, R., & Titherington, M. (2004). Chloride resistance of high-performance concretes subjected to accelerated curing. *Cement and Concrete Research, 34*(9), 1561-1567.

Hossain, Ahmed, S., & Lachemi, M. (2011). Lightweight concrete incorporating pumice based blended cement and aggregate: Mechanical and durability characteristics. *Construction and Building Materials, 25*(3), 1186-1195.

Hossain, A., & Khandaker, M. (2004). Properties of volcanic pumice based cement and lightweight concrete. *Cement and Concrete Research, 34*(2), 283-291.

Hosseini, S. E., & Wahid, M. A. (2012). Necessity of biodiesel utilization as a source of renewable energy in Malaysia. *Renewable and Sustainable Energy Reviews, 16*(8), 5732-5740.

Hosseini, S. E., & Wahid, M. A. (2014). Utilization of palm solid residue as a source of renewable and sustainable energy in Malaysia. *Renewable and Sustainable Energy Reviews, 40*, 621-632.

Huang, C.-H., & Wang, S.-Y. (2013). Application of water treatment sludge in the manufacturing of lightweight aggregate. *Construction and Building Materials, 43*, 174-183.

Huntzinger, D. N., & Eatmon, T. D. (2009). A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies. *Journal of Cleaner Production, 17*(7), 668-675.

Hussein, S. H., & Muda, K. N. B. M. C. (2012). Modeling of Ultimate Load For Lightweight Palm Oil Clinker Reinforced Concrete Beams With Web Openings Using Response Surface Methodology. *International Journal of Civil Engineering, 3*(1), 33-44.

Hwang, C.-L., Bui, L. A.-T., Lin, K.-L., & Lo, C.-T. (2012). Manufacture and performance of lightweight aggregate from municipal solid waste incinerator fly ash and reservoir sediment for self-consolidating lightweight concrete. *Cement and Concrete Composites, 34*(10), 1159-1166.

Hwang, C.-L., & Hung, M.-F. (2005). Durability design and performance of self-consolidating lightweight concrete. *Construction and Building Materials, 19*(8), 619-626.

Ismail, Z. Z., & Al-Hashmi, E. A. (2008). Use of waste plastic in concrete mixture as aggregate replacement. *Waste management, 28*(11), 2041-2047.

Jegathish, K. (2016). *Feasibility study of palm oil clinker as environmentally friendly self-compacting concrete/Jegathish Kanadasan.* University of Malaya.

Jepsen, M. T., Mathiesen, D., Munch-Petersen, C., & Bager, D. (2001). *Durability of resource saving "Green" type of concrete.* Paper presented at the Proceedings of the FIB-Symposium on Concrete and Environment, Berlin.

Jiang, L., Liu, Z., & Ye, Y. (2004). Durability of concrete incorporating large volumes of low-quality fly ash. *Cement and Concrete Research, 34*(8), 1467-1469.

Johari, M. M., Zeyad, A., Bunnori, N. M., & Ariffin, K. (2012). Engineering and transport properties of high-strength green concrete containing high volume of ultrafine palm oil fuel ash. *Construction and Building Materials, 30*, 281-288.

Joshi, P., & Chan, C. (2002). Rapid chloride permeability testing. *Concrete Construction, 47*(12), 37-43.

Jumaat, M. Z., Alengaram, U. J., & Mahmud, H. (2009). Shear strength of oil palm shell foamed concrete beams. *Materials & Design, 30*(6), 2227-2236.

Kan, A., & Demirboğa, R. (2009). A novel material for lightweight concrete production. *Cement and Concrete Composites, 31*(7), 489-495.

Kanadasan, J., & Abdul Razak, H. (2015a). Engineering and sustainability performance of self-compacting palm oil mill incinerated waste concrete. *Journal of Cleaner Production, 89*, 78-86.

Kanadasan, J., & Abdul Razak, H. (2015b). Utilization of Palm Oil Clinker as Cement Replacement Material. *Materials, 8*(12), 8817-8838.

Kanadasan, J., Fauzi, A. F. A., Razak, H. A., Selliah, P., Subramaniam, V., & Yusoff, S. (2015). Feasibility studies of palm oil mill waste aggregates for the construction industry. *Materials, 8*(9), 6508-6530.

Kanadasan, J., & Razak, H. A. (2014a). *Fresh properties of self-compacting concrete incorporating palm oil clinker*. Paper presented at the InCIEC 2013, Springer, Singapor.

Kanadasan, J., & Razak, H. A. (2014b). Mix design for self-compacting palm oil clinker concrete based on particle packing. *Materials & Design, 56*, 9-19.

Kanadasan, J., & Razak, H. A. (2015). Engineering and sustainability performance of self-compacting palm oil mill incinerated waste concrete. *Journal of Cleaner Production, 89*, 78-86.

Karim, M. R., Hashim, H., & Razak, H. A. (2016). Assessment of pozzolanic activity of palm oil clinker powder. *Construction and Building Materials*, *127*, 335-343.

Katz, A. (2003). Properties of concrete made with recycled aggregate from partially hydrated old concrete. *Cement and Concrete Research, 33*(5), 703-711.

Khademi, F., Akbari, M., & Jamal, S. M. (2015). Measuring Compressive Strength of Puzzolan Concrete by Ultrasonic Pulse Velocity Method. *i-Manager's Journal on Civil Engineering, 5*(3), 23-30.

Khaleel, O. R., Al-Mishhadani, S. A., & Abdul Razak, H. (2011). The Effect of Coarse Aggregate on Fresh and Hardened Properties of Self-Compacting Concrete (SCC). *Procedia Engineering, 14*, 805-813.

Khaloo, A. R., Dehestani, M., & Rahmatabadi, P. (2008). Mechanical properties of concrete containing a high volume of tire–rubber particles. *Waste management, 28*(12), 2472-2482.

Khokhar, M., Rozière, E., Turcry, P., Grondin, F., & Loukili, A. (2010). Mix design of concrete with high content of mineral additions: optimisation to improve early age strength. *Cement and Concrete Composites*, *32*(5), 377-385.

Kılıç, A., Atiş, C. D., Yaşar, E., & Özcan, F. (2003). High-strength lightweight concrete made with scoria aggregate containing mineral admixtures. *Cement and Concrete Research, 33*(10), 1595-1599.

Kockal, N. U., & Ozturan, T. (2011). Strength and elastic properties of structural lightweight concretes. *Materials & Design, 32*(4), 2396-2403.

Koehler, E. P., & Fowler, D. W. (2003). Summary of concrete workability test methods. *International Center for Aggregates Research, 105*, 4-8.

Kohno, K., Okamoto, T., Isikawa, Y., Sibata, T., & Mori, H. (1999). Effects of artificial lightweight aggregate on autogenous shrinkage of concrete. *Cement and Concrete Research*, *29*(4), 611-614.

Koide, H., Tomon, M., & Sasaki, T. (2002). *Investigation of the use of waste plastic as an aggregate for lightweight concrete.* Paper presented at the Challenges of Concrete Construction: Volume 5, Sustainable Concrete Construction: Proceedings of the International Conference held at the University of Dundee, Scotland, UK on 9–11 September 2002.

Krizova, K., & Hela, R. (2014). Selected Technological Factors Influencing the Modulus of Elasticity of Concrete. *World Academy of Science, Engineering and Technology, International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering, 8*(6), 593-595.

Li, G., Zhao, Y., Pang, S.-S., & Li, Y. (1999). Effective Young's modulus estimation of concrete. *Cement and Concrete Research, 29*(9), 1455-1462.

Limbachiya, M. C. (2009). Bulk engineering and durability properties of washed glass sand concrete. *Construction and Building Materials, 23*(2), 1078-1083.

Lo, HZ, C., & ZG, L. (2004). Influence of aggregate pre-wetting and fly ash on mechanical properties of lightweight concrete. *Waste management, 24*(4), 333-338.

Lo, T., & Cui, H. (2004). Effect of porous lightweight aggregate on strength of concrete. *Materials letters, 58*(6), 916-919.

Lotfi, S., Deja, J., Rem, P., Mróz, R., van Roekel, E., & van der Stelt, H. (2014). Mechanical recycling of EOL concrete into high-grade aggregates. *Resources, conservation and Recycling, 87*, 117-125.

Mahmud, H. (2008). Ductility behaviour of reinforced palm kernel shell concrete beams. *European Journal of Scientific Research, 23*(3), 406-420.

Mangulkar, M., & Jamkar, S. (2013). Review of Particle Packing Theories Used For Concrete Mix Proportioning. *International Journal Of Scientific & Engineering Research, 4*(5), 143-148.

Mannan, Alexander, J., Ganapathy, C., & Teo, D. (2006). Quality improvement of oil palm shell (OPS) as coarse aggregate in lightweight concrete. *Building and Environment, 41*(9), 1239-1242.

Mannan, & Ganapathy, C. (2002). Engineering properties of concrete with oil palm shell as coarse aggregate. *Construction and Building Materials, 16*(1), 29-34.

Mannan, & Ganapathy, C. (2004). Concrete from an agricultural waste-oil palm shell (OPS). *Building and Environment, 39*(4), 441-448.

Mannan, & Neglo, K. (2010). Mix design for oil-palm-boiler clinker (OPBC) concrete. *Journal of Science and Technology, 30*(1), 111-118.

Mateus, R., Neiva, S., Bragança, L., Mendonça, P., & Macieira, M. (2013). Sustainability assessment of an innovative lightweight building technology for partition walls – Comparison with conventional technologies. *Building and Environment, 67*, 147-159.

Mazloom, M., Ramezanianpour, A., & Brooks, J. (2004). Effect of silica fume on mechanical properties of high-strength concrete. *Cement and Concrete Composites, 26*(4), 347-357.

Meador, M. R., & Layher, A. O. (1998). Instream sand and gravel mining: environmental issues and regulatory process in the United States. *Fisheries, 23*(11), 6-13.

Meddah, M. S., & Bencheikh, M. (2009). Properties of concrete reinforced with different kinds of industrial waste fibre materials. *Construction and Building Materials, 23*(10), 3196-3205.

Meddah, M. S., Zitouni, S., & Belâabes, S. (2010). Effect of content and particle size distribution of coarse aggregate on the compressive strength of concrete. *Construction and Building Materials, 24*(4), 505-512.

Meyer, C. (2009). The greening of the concrete industry. *Cement and Concrete Composites, 31*(8), 601-605.

Mohammed, B. S., Al-Ganad, M. A., & Abdullahi, M. (2011). Analytical and experimental studies on composite slabs utilising palm oil clinker concrete. *Construction and Building Materials, 25*(8), 3550-3560.

Mohammed, B. S., Foo, W., & Abdullahi, M. (2014). Flexural strength of palm oil clinker concrete beams. *Materials & Design, 53*, 325-331.

Mokhtarzadeh, A., & French, C. (2000). Mechanical properties of high-strength concrete with consideration for precast applications. *Materials Journal, 97*(2), 136-147.

Moosberg-Bustnes, H., Lagerblad, B., & Forssberg, E. (2004). The function of fillers in concrete. *Materials and structures, 37*(2), 74-81.

Mun, K. (2007). Development and tests of lightweight aggregate using sewage sludge for nonstructural concrete. *Construction and Building Materials, 21*(7), 1583-1588.

Naik, T. R., Singh, S. S., & Hossain, M. M. (1994). Permeability of concrete containing large amounts of fly ash. *Cement and Concrete Research, 24*(5), 913-922.

Nash't, I. H., A'bour, S. H., & Sadoon, A. A. (2005). *Finding an unified relationship between crushing strength of concrete and non-destructive tests.* Paper presented at the Middle East Nondestructive Testing Conference & Exhibition, Bahrain.

Neville. (2008). Properties of concrete. 14th ed., Prentice Hall, Malaysia.

Nilson, A. H., & Martinez, S. (1986). Mechanical properties of high-strength lightweight concrete. *Journal Proceedings, 83*(4), 606-613.

Noguchi, T., Tomosawa, F., Nemati, K. M., Chiaia, B. M., & Fantilli, A. P. (2009). A practical equation for elastic modulus of concrete. *ACI Structural Journal, 106*(5), 690.

Ohimain, I., Bassey, S., & Bawo, D. (2009). Uses of seas shells for civil construction works in coastal Bayelsa State, Nigeria: A waste management perspective. *Research Journal of Biological Sciences, 4*(9), 1025-1031.

Okafor, F. O. (1988). Palm kernel shell as a lightweight aggregate for concrete. *Cement and Concrete Research, 18*(6), 901-910.

Ozbakkaloglu, T., Gu, L., & Pour, A. F. (2016). Normal-and high-strength concretes incorporating air-cooled blast furnace slag coarse aggregates: Effect of slag size and content on the behavior. *Construction and Building Materials, 126*, 138-146.

Papadakis, V. G. (2000). Effect of supplementary cementing materials on concrete resistance against carbonation and chloride ingress. *Cement and Concrete Research, 30*(2), 291-299.

Paris, J. M., Roessler, J. G., Ferraro, C. C., DeFord, H. D., & Townsend, T. G. (2016). A review of waste products utilized as supplements to Portland cement in concrete. *Journal of Cleaner Production, 121*, 1-18.

Perraton, D., Aiticin, P., & Vezina, D. (1988). Permeabilities of silica fume concrete. *Special Publication, 108*, 63-84.

Polat, R., Demirboğa, R., Karakoç, M. B., & Türkmen, İ. (2010). The influence of lightweight aggregate on the physico-mechanical properties of concrete exposed to freeze–thaw cycles. *Cold Regions Science and Technology, 60*(1), 51-56.

Poon, C. S., Kou, S. C., & Lam, L. (2006). Compressive strength, chloride diffusivity and pore structure of high performance metakaolin and silica fume concrete. *Construction and Building Materials, 20*(10), 858-865.

Qiao, X., Ng, B., Tyrer, M., Poon, C., & Cheeseman, C. (2008). Production of lightweight concrete using incinerator bottom ash. *Construction and Building Materials, 22*(4), 473-480.

Qing, Y., Zenan, Z., Deyu, K., & Rongshen, C. (2007). Influence of nano-SiO_2 addition on properties of hardened cement paste as compared with silica fume. *Construction and Building Materials, 21*(3), 539-545.

Rao, A., Jha, K. N., & Misra, S. (2007). Use of aggregates from recycled construction and demolition waste in concrete. *Resources, conservation and Recycling, 50*(1), 71-81.

Rashid, M. A., & Mansur, M. A. (2009). Considerations in producing high strength concrete. *Journal of civil engineering (IEB), 37*(1), 53-63.

Rashid, M. A., Salam, M. A., Shill, S. K., & Hasan, M. K. (2012). Effect of replacing natural coarse aggregate by brick aggregate on the properties of concrete. *Dhaka University Engineering Technolgy, 1*(3), 17-22.

Richardson, A., Allain, P., & Veuille, M. (2010). Concrete with crushed, graded and washed recycled construction demolition waste as a coarse aggregate replacement. *Structural Survey, 28*(2), 142-148.

Rosković, R., & Bjegović, D. (2005). Role of mineral additions in reducing CO_2 emission. *Cement and Concrete Research, 35*(5), 974-978.

Roslli, W. O., Mohamed, N., & Mohamed, N. (2002). The performance of pretensioned prestressed concrete beams made with lightweight concrete. *Jurnal Kejuruteraan Awam, 14*(1), 60-70.

Safiuddin, M., Raman, S., & Zain, M. (2007). Utilization of quarry waste fine aggregate in concrete mixtures. *Journal of Applied Sciences Research, 3*(3), 202-208.

Sagoe-Crentsil, K. K., Brown, T., & Tayler, A. (2002). *Durability and performance characteristics of recycled aggregate concrete.* Paper presented at the Proceedings of the 9th international conference on durability of Materials and Components, Brisbane, Australien.

Sagoe-Crentsil, K. K., Brown, T., & Taylor, A. H. (2001). Performance of concrete made with commercially produced coarse recycled concrete aggregate. *Cement and concrete research, 31*(5), 707-712.

Sandvik, M., & Gjorv, O. E. (1992). Prediction of strength development for silica fume concrete. *Special Publication, 132*, 987-996.

Sanjuan, M. A., Argiz, C., Galvez, J. C., & Moragues, A. (2015). Effect of silica fume fineness on the improvement of Portland cement strength performance. *Construction and Building Materials, 96*, 55-64.

Sata, V., Jaturapitakkul, C., & Kiattikomol, K. (2007). Influence of pozzolan from various by-product materials on mechanical properties of high-strength concrete. *Construction and Building Materials, 21*(7), 1589-1598.

Senthamarai, R., & Manoharan, P. D. (2005). Concrete with ceramic waste aggregate. *Cement and Concrete Composites, 27*(9), 910-913.

Shafigh, P., Jumaat, M. Z., & Mahmud, H. (2010). Mix design and mechanical properties of oil palm shell lightweight aggregate concrete: a review. *International journal of the physical sciences, 5*(14), 2127-2134.

Shafigh, P., Jumaat, M. Z., Mahmud, H. B., & Hamid, N. A. A. (2012). Lightweight concrete made from crushed oil palm shell: tensile strength and effect of initial curing on compressive strength. *Construction and Building Materials, 27*(1), 252-258.

Shi, C. (2004). Effect of mixing proportions of concrete on its electrical conductivity and the rapid chloride permeability test (ASTM C1202 or ASSHTO T277) results. *Cement and Concrete Research, 34*(3), 537-545.

Shi, C., Wu, Z., Xiao, J., Wang, D., Huang, Z., & Fang, Z. (2015). A review on ultra high performance concrete: Part I. Raw materials and mixture design. *Construction and Building Materials, 101*, 741-751.

Siddique, R. (2003). Effect of fine aggregate replacement with Class F fly ash on the mechanical properties of concrete. *Cement and Concrete Research, 33*(4), 539-547.

Siddique, R. (2011). Utilization of silica fume in concrete: Review of hardened properties. *Resources, conservation and Recycling, 55*(11), 923-932.

Smadi, M., & Migdady, E. (1991). Properties of high strength tuff lightweight aggregate concrete. *Cement and Concrete Composites, 13*(2), 129-135.

Sobolev, K. (2004). The development of a new method for the proportioning of high-performance concrete mixtures. *Cement and Concrete Composites, 26*(7), 901-907.

Suwanvitaya, P., Jiravetakul, S., Vanichavetin, C. (2006). effect of aggregate function on concrete strength. *Symposium on Infrastructure Development and Environment*.

Suzuki, M., Seddik Meddah, M., & Sato, R. (2009). Use of porous ceramic waste aggregates for internal curing of high-performance concrete. *Cement and Concrete Research, 39*(5), 373-381.

Swamy, R., & Mahmud, H. (1986). Mix proportions and strength characteristics of concrete containing 50 percent low-calcium fly ash. *Special Publication, 91*, 413-432.

Tangchirapat, W., Jaturapitakkul, C., & Chindaprasirt, P. (2009). Use of palm oil fuel ash as a supplementary cementitious material for producing high-strength concrete. *Construction and Building Materials, 23*(7), 2641-2646.

Tangchirapat, W., Saeting, T., Jaturapitakkul, C., Kiattikomol, K., & Siripanichgorn, A. (2007). Use of waste ash from palm oil industry in concrete. *Waste management, 27*(1), 81-88.

Tasnimi, A. (2004). Mathematical model for complete stress–strain curve prediction of normal, light-weight and high-strength concretes. *Magazine of Concrete Research, 56*(1), 23-34.

Tennis, P. D., & Jennings, H. M. (2000). A model for two types of calcium silicate hydrate in the microstructure of Portland cement pastes. *Cement and Concrete Research, 30*(6), 855-863.

Teo, D., Mannan, M., & Kurian, V. (2006). Structural concrete using oil palm shell (OPS) as lightweight aggregate. *Turkish Journal of Engineering and Environmental Sciences, 30*(4), 251-257.

Teo, D., Mannan, M., & Kurian, V. (2010). Durability of lightweight OPS concrete under different curing conditions. *Materials and structures, 43*(1-2), 1-13.

Teo, D., Mannan, M. A., Kurian, V., & Ganapathy, C. (2007). Lightweight concrete made from oil palm shell (OPS): structural bond and durability properties. *Building and Environment, 42*(7), 2614-2621.

Topcu, I. B. (1997). Physical and mechanical properties of concretes produced with waste concrete. *Cement and concrete research, 27*(12), 1817-1823.

Trtnik, G., Kavčič, F., & Turk, G. (2009). Prediction of concrete strength using ultrasonic pulse velocity and artificial neural networks. *Ultrasonics, 49*(1), 53-60.

Turgut, P. (2004). Evaluation of the ultrasonic pulse velocity data coming on the field. *4th International Conference on NDE in Relation to Structural Integrity for Nuclear and Pressuised Components, 6*, 573-578.

Uysal, M., Yilmaz, K., & Ipek, M. (2012). The effect of mineral admixtures on mechanical properties, chloride ion permeability and impermeability of self-compacting concrete. *Construction and Building Materials, 27*(1), 263-270.

Wang, S., Llamazos, E., Baxter, L., & Fonseca, F. (2008). Durability of biomass fly ash concrete: freezing and thawing and rapid chloride permeability tests. *Fuel, 87*(3), 359-364.

Wee, T., Suryavanshi, A. K., & Tin, S. (2000). Evaluation of rapid chloride permeability test (RCPT) results for concrete containing mineral admixtures. *Materials Journal, 97*(2), 221-232.

Wongkeo, W., Thongsanitgarn, P., Ngamjarurojana, A., & Chaipanich, A. (2014). Compressive strength and chloride resistance of self-compacting concrete containing high level fly ash and silica fume. *Materials & Design, 64*, 261-269.

Wu, K.-R., Chen, B., Yao, W., & Zhang, D. (2001). Effect of coarse aggregate type on mechanical properties of high-performance concrete. *Cement and Concrete Research, 31*(10), 1421-1425.

Yazıcı, H. (2008). The effect of silica fume and high-volume Class C fly ash on mechanical properties, chloride penetration and freeze–thaw resistance of self-compacting concrete. *Construction and Building Materials, 22*(4), 456-462.

Ylmén, R., Jäglid, U., Steenari, B.-M., & Panas, I. (2009). Early hydration and setting of Portland cement monitored by IR, SEM and Vicat techniques. *Cement and Concrete Research, 39*(5), 433-439.

Yoon, G.-L., Kim, B.-T., Kim, B.-O., & Han, S.-H. (2003). Chemical–mechanical characteristics of crushed oyster-shell. *Waste management, 23*(9), 825-834.

Yuan, R. L., & Cook, J. E. (1983). Study of a class C fly ash concrete. *Special Publication, 79*, 307-320.

Zakaria, M. L. (1986). Strength properties of oil palm clinker concrete. *Jurnal Teknologi, 8*(1), 28-37.

Zhang, B., & Poon, C. S. (2015). Use of furnace bottom ash for producing lightweight aggregate concrete with thermal insulation properties. *Journal of Cleaner Production, 99*, 94-100.

Zhutovsky, S., Kovler, K., & Bentur, A. (2004). Influence of cement paste matrix properties on the autogenous curing of high-performance concrete. *Cement and Concrete Composites, 26*(5), 499-507.

LIST OF PUBLICATIONS

1. **Effect of Palm Oil Clinker (POC) Aggregates on Fresh and Hardened Properties of Concrete**
   Fuad Abutaha, Razak, H. A., & Kanadasan, J. (2016). Construction and Building Materials, 112, 416-423.

2. **Effect of Coating Palm Oil Clinker Aggregate on the Engineering Properties of Normal Grade Concrete**
   Fuad Abutaha, Abdul Razak, H., & Ibrahim, H. A. (2017). Coatings, 7(10), 175.

3. **Adopting Particle-packing Method to Develop High Strength Palm Oil Clinker Concrete.**
   Fuad Abutaha, Abdul Razak, H., & Ibrahim, H. A, Haider Hamad (2018). Resources, Conservation and Recycling, 131, 247–258.